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Towards Indicators of Soil Health

Project Report

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Summary

This report sets out the approach which aimed to pave the way for an indicator framework of soil health for England. The study developed a concept for soil health indicators and how they could be presented, before trialling the process through a 'proof-of-concept', resulting in an interactive dashboard displaying soils' ability to contribute to the delivery of selected ecosystem services as demonstration indicators of soil health.

Healthy soil contributes to a wide range of ecosystem services, such as food provision, climate, and water regulation, and are relevant across a wide range of policy areas in England. The ability to assess the health of soil, both from a national perspective and the perspective of an individual landowner or manager is therefore important as a first step to be able to maintain or enhance delivery of these services. In the context of Defra and its Arm's Length Bodies (ALBs) developing schemes to monitor soil parameters, it is important to ensure that the most useful data are collected, and that once collected, data have maximum utility through clear interpretation and communication. This study informed both these aspects by setting out and trialling an approach to review soil parameters that are best able to contribute to indicators, and to develop models to process available information to produce ecosystem service-oriented indicators.

Land is managed for divergent and often multiple outcomes, and management decisions will have different impacts on different ecosystem services, with trade-offs often involved. Therefore, an indicator intended to present soil health for a range of ecosystem services, displayed in parallel, will allow stakeholders the ability to focus on particular outcomes of interest, whilst still considering the wider range of ecosystem services.

The process (Figure 1) involves systematically reviewing the links between soil properties and ecosystem services, using literature review and expert knowledge to create ecological models for each ecosystem service. This approach also connects the different recorded soil metrics and other parameters (e.g. climate variables), before turning these into statistical models populated with relevant national datasets and best understanding of relationships between model nodes. The resulting outputs give an indication of soil health in relation to a particular ecosystem service for any selected land parcel, with the ability to contextualise it; the output can be considered in relation to the total range of values possible across soils with similar inherent properties across all land uses, or when restricted to the current land use.

Another important concept is the ability to refine the indicator with local knowledge. This could be through, where appropriate, entering direct recorded soil metrics into the model and/or through incorporating knowledge of local land management options. This would enable users to get a more accurate view of the status of their selected land parcel and explore how implementing different management options would impact the soil health of their site across the range of ecosystem services.

To aid these applications it is proposed that the indicators are presented in an interactive dashboard app. Users would be able to select a land parcel of interest, optionally toggle on/off land management options and add other selected local data. The display would include indicators for that site, contextualised for a range of ecosystem services.

The project trialled producing indicators for selected ecosystem services as a proof-of-concept. The study considered the contribution that soil made to four key ecosystem services based on established scientific relationships. These are climate regulation 'through soil carbon storage'; water regulation 'through soil's contribution to runoff reduction'; maintenance of biodiversity 'through soil biodiversity'; and food and fibre production potential 'through soil's contribution to land capability for agriculture'. For the first two of these,

demonstration statistical models were completed, resulting in soil health indicators presented in a dashboard app.

By considering how similar complex indicator or system issues have been tackled previously, the importance of starting with the knowledge available and refining solutions through time was apparent. This study recommends several steps to move from the concept towards a functional, reliable, and meaningful set of indicators. All components of the proof of concept (Figure 1) can be upgraded as knowledge improves. Examples include: the sift of soil properties with proven relationships to ecosystem services can be re-run to pick up new research; the models of soil function can be improved with wider expert and science input; the modelling technique (currently Bayesian) can be adapted, and more empirical elements can be added as more soil data becomes available; and the functionality of the dashboard and way the indicators are presented can be refined.

Clear communication and guidance on how to best use the indicators will be key to achieving buy-in, particularly considering the balance of prioritising soil health in relation to one particular ecosystem service, whilst considering the impact on other ecosystem services.

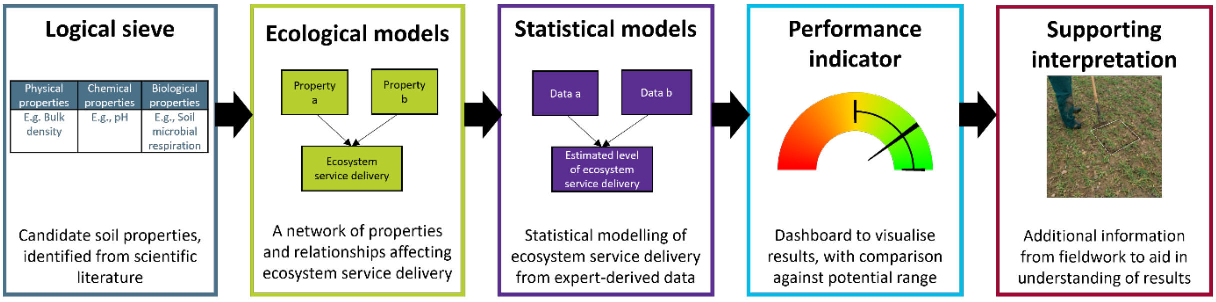

Figure 1. The general approach taken within the proof-of-concept (described in more detail in Section 4).

Contents

1 Policy context

Healthy soil is essential to delivering a myriad of ecosystem services and outcomes, including climate regulation (through soil carbon storage), food/fibre production potential (through soils' contribution to land capability for agriculture), maintenance of biodiversity (through increased abundance, diversity, connectivity and functionality of soil organisms) and water regulation (through soils' contribution to runoff reduction). The Government's 25 Year Environment Plan (Defra 2018) recognised 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 2023), is the first revision to the 25 Year Plan. It reiterates the importance of soil and how this vital natural resource will be managed. It sets out a new target to bring at least 40% of England's agricultural soil into sustainable management by 2028 through new farming schemes and increase that to 60% by 2030. The EIP also commits to several factors that will establish comprehensive baseline data including to "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 ("There are insufficient data on the health of our soils."). The Sustainable Farming Incentive (SFI) (UK Government 2021a) also notes the importance of soil. Under SFI, farmers are rewarded for actions that protect the soil from erosion, help to increase soil organic matter, and enable the plants and organisms that live in the soil to function effectively.

Defra's Natural Capital and Ecosystem Assessment (NCEA) programme also has soil health as a key focus. NCEA will provide high quality data to assess the state and condition of natural capital assets, ecosystems, and biodiversity in terrestrial and freshwater environments. As part of this, up-to-date and comprehensive soil health data is a priority of the programme and being measured through projects such as the strategically sampled England Ecosystem Survey and the England Peat Map. The data, evidence-based insight and understanding NCEA will deliver will inform ambitious, proactive and sustainable policy decisions to support the government's goal to improve the state of the environment within a generation. This includes supporting the Environment Act Targets, 25-Year Environment Plan and programmes such as the Environmental Land Management Schemes.

One of NCEA's five objectives relates to understanding soil carbon stocks. The role of carbon in climate change is another high priority area of policy, addressed by key publications such as the Net Zero Strategy (UK Government 2021b). The Net Zero Strategy makes numerous references to soil (especially peat soils) and their potential to help meet published targets, via carbon sequestration and storage.

Overall, soil health is relevant across a wide range of policy areas and is directly referenced in numerous recent high-profile policy documents. A common theme across these documents is the need to develop indicators of soil health based on sound measurements and monitoring, to better inform decisions on protecting and enhancing natural capital. This proof-of-concept project aims to outline a conceptual framework as a first step towards fulfilling this clear policy need.

2 Overall requirement

An ideal set of soil health indicators would allow users to:

- Understand the performance of soil functions in terms of its actual and potential ability to contribute to delivering ecosystem services, with an indicator developed for each ecosystem service to enable assessment of trade-offs.
- Integrate data from soil monitoring to understand changes in soil health over time (for example from annual to decadal changes) as the indicator is routinely updated with the latest data, reflecting their increasing, or decreasing ability to help deliver ecosystem services.
- Obtain information at a variety of different spatial scales (from an individual land parcel to nationwide).
- Understand how the effects of land management and land-use change could affect soils' contribution to the delivery of ecosystem services.

3 Proposed solution

In this study soil health was defined as the ability of soils to perform their functions and to contribute to the delivery of ecosystem goods and services. It is noted that soils at different locations have differing inherent underlying constraints and are subject to different land uses and climate. The range of soil functions and ecosystem services provided should reflect the different capabilities of different soils – an overall 'healthy' soil is therefore one in which ecosystem services are delivered, whilst taking account of inherent underlying constraints and land use (Figure 2).

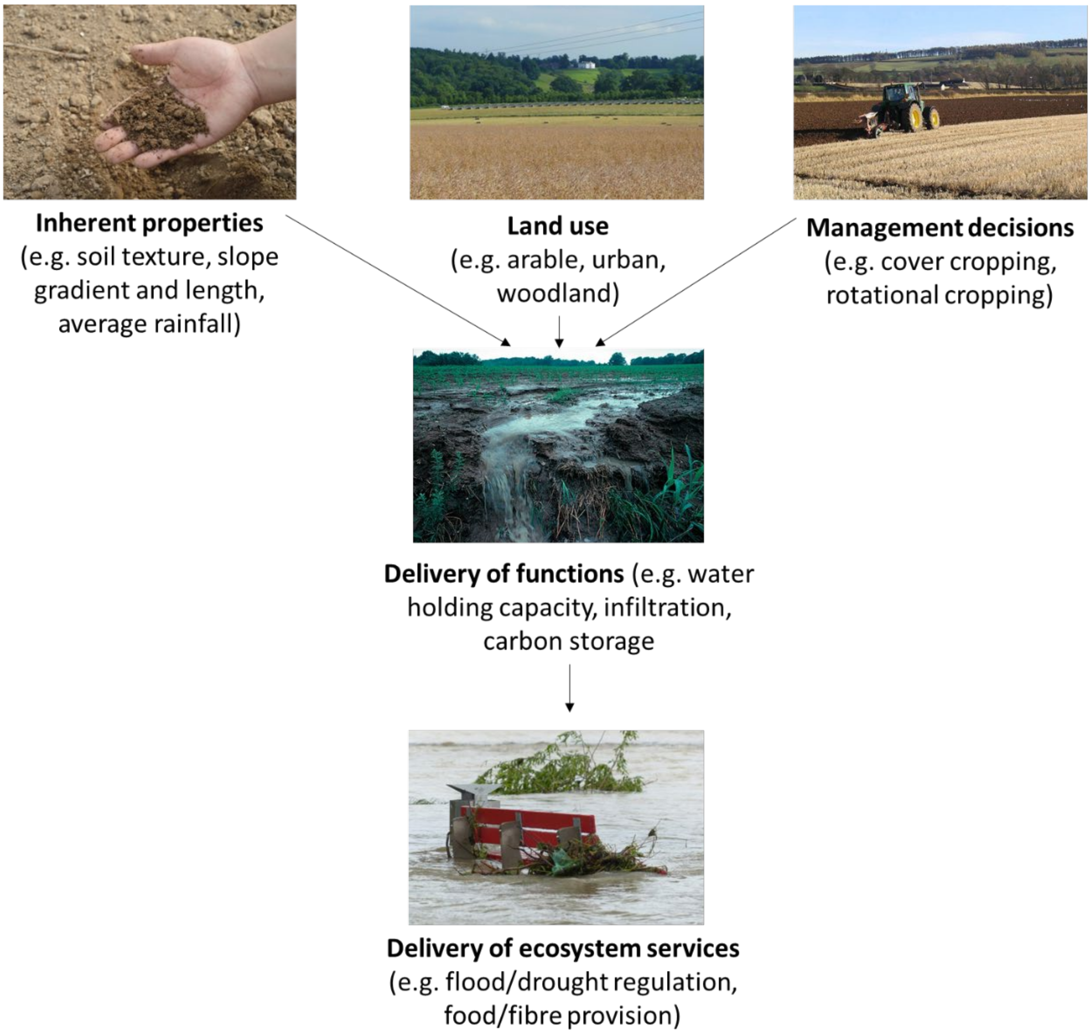

Figure 2. Factors affecting soils' ability to perform functions and contribute to delivery of ecosystem services. Factors range from inherent site properties (that are not possible to directly influence) and land use (which may have limited scope to change) to land management decisions (which are relatively easy to change to influence soil health). Knowledge of these factors is required to understand whether measured soil properties show the performance of that soil to be higher or lower than expected. Photo attributions: Jonathan Billinger / Layers of land use / CC BY-SA 2.0; Walter Baxter / Ploughing a field / CC BY-SA 2.0; U.S. Department of Agriculture, Natural Resources Conservation Service / Runoff; no attribution required for other photos.

Some land uses are naturally more suited to providing some ecosystem services than others (e.g. semi-natural grasslands compared to built-up urban areas), and some are better at providing multiple services. However, usually there is limited scope to change land use. Changes in land management practices can impact the health of soils at a site and are more achievable in a wider range of circumstances. It was important for any soil indicator(s) to be framed in a way that captured the potential of soils to deliver ecosystem services, bearing in mind the constraints.

Expert knowledge demonstrated that it was not possible to distil ‘soil health’ into a single ‘indicator’ in a manner that would be practically useful, as different soils may be best suited and managed to perform different functions, so supporting different ecosystem services. Hence describing a soil’s ‘health’ or ‘quality’ in relation to particular ecosystem services of interest, and acknowledgement of trade-offs required in managing soils to promote certain ecosystem services provides part of this indicator. However, to get a fuller understanding of the soil health of a particular site, it is important to consider soil health in relation to a range of ecosystem services. A set of indicators focussed on a range of ecosystem services are therefore proposed. This will provide a flexible framework for stakeholders to focus on their particular ecosystem service of interest, whilst at the same time presenting this in a wider context.

To meet the project’s overall requirements, the indicator set also needs to be designed in a way that is scalable, so it is applicable both nationally and at an individual site level. It should allow users to both make use of available data and input their own site-based data, to model soils’ contribution to the delivery of a selection of ecosystem services with precision, relevant to their particular site of interest.

In summary, the vision for the proposed set of soil health indicators is one that:

- Presents results in a visually engaging way that not only shows soils’ estimated contribution to ecosystem service delivery (given the data available and land management decisions that have taken place), but also shows how results compare to expectations given the inherent site properties (e.g. soil type), and land use of a selected location.
- Presents soil health in relation to a range of ecosystem services, allowing users to focus on a particular service of interest whilst still viewing the wider context to include other services.
- Allows users to view results at a range of scales and enables them to input their own local data (e.g. around land-management options) to refine the indicator outputs for their own site of interest or see the impacts of different land management / land-use options.

Figure 3 shows a proposed way of presenting this information through means of speedometer-type dials to show the soil health of a land parcel in relation to particular ecosystem services. Each dial on the dashboard represents one ecosystem service to allow for an assessment of trade-offs and synergies. The dial would not only show the absolute level of ‘soil health’ in relation to that particular ecosystem service but would also show the range of what would be expected for soils with the same inherent properties and land use. This enables users to better understand how their site is performing relative to other similar sites. Whilst the proof-of-concept study had to present a slightly simpler visualisation (see ‘Visualising results’ section) due to constraints on data, the original concept is presented here as the ultimate vision for the indicator, subject to more data becoming available.

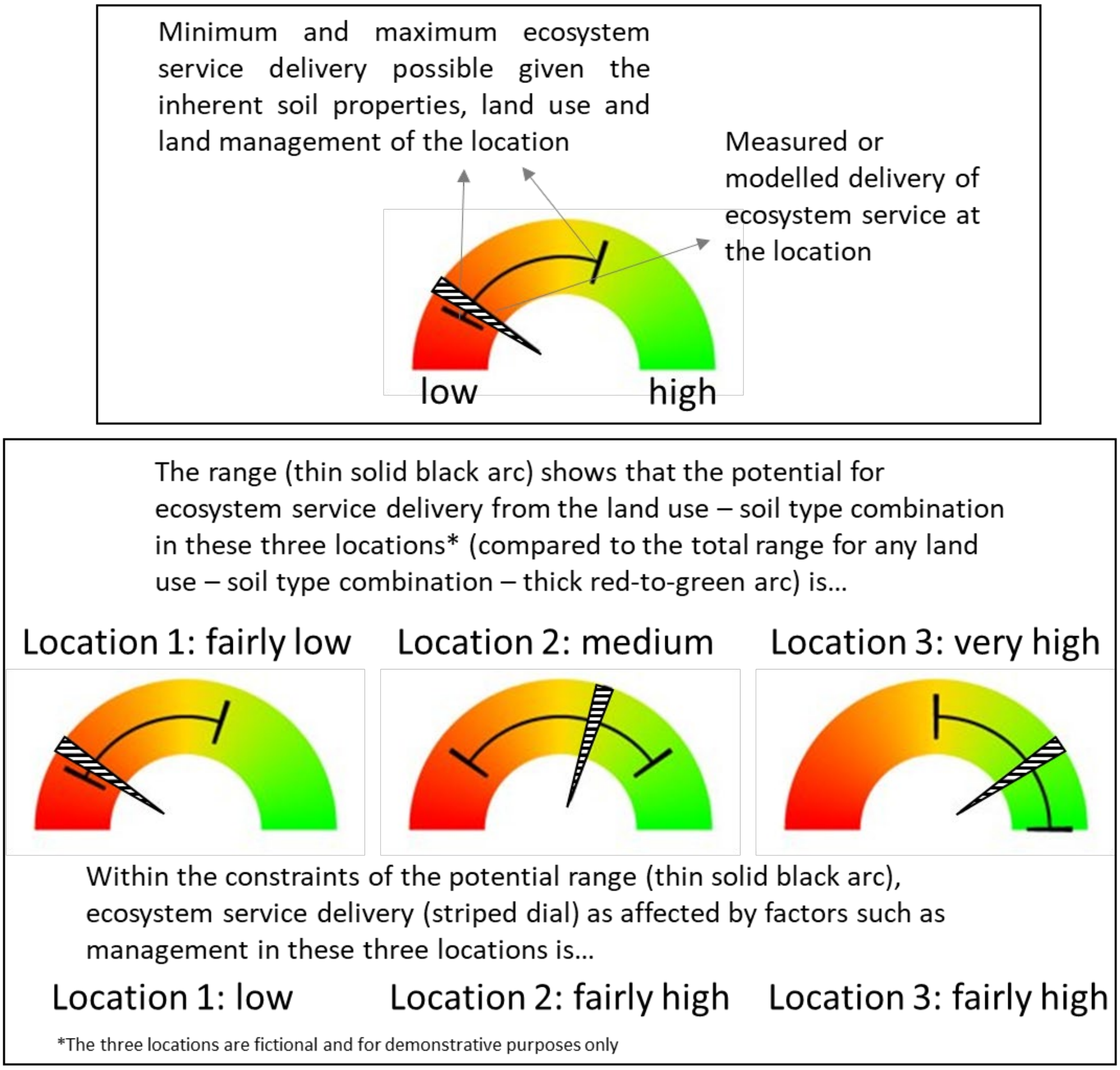

Figure 3. An explanation of a proposed indicator visualisation concept that could illustrate: (a) estimated delivery values for a given ecosystem service (represented by the striped line within each dial); (b) where this falls within the range of possible values across all locations (the total range, represented by the thick red-green arc making up each dial, with the minimum at the far left and the maximum at the far right); (c) where this falls within the range of possible values given the constraints of the land-use-soil type combination of the location (represented by the thin solid black line within each dial). Each ecosystem service (climate regulation, water regulation, etc.) would have a separate visualisation. Multiple dials of this design would be presented alongside each other (one for each ecosystem service), in order to allow for an assessment of trade-offs and synergies.

3.1 Challenges and constraints

The proposed solution and vision are ambitious and will be constrained by the data and knowledge currently available. National datasets are not available for many of the relevant soil variables that should be included in the indicator (see Annex 1). The first iteration will therefore not fulfil all requirements but will provide a starting point and highlight the monitoring and research needed to improve the outputs in subsequent iterations. Research into previous projects developing indicators of complex systems highlights that this iterative process is necessary in order to make progress – it will not be possible to reach an accepted solution without first producing a more basic version for consultation and consequent improvement (see Annex 2 and Figure 4).

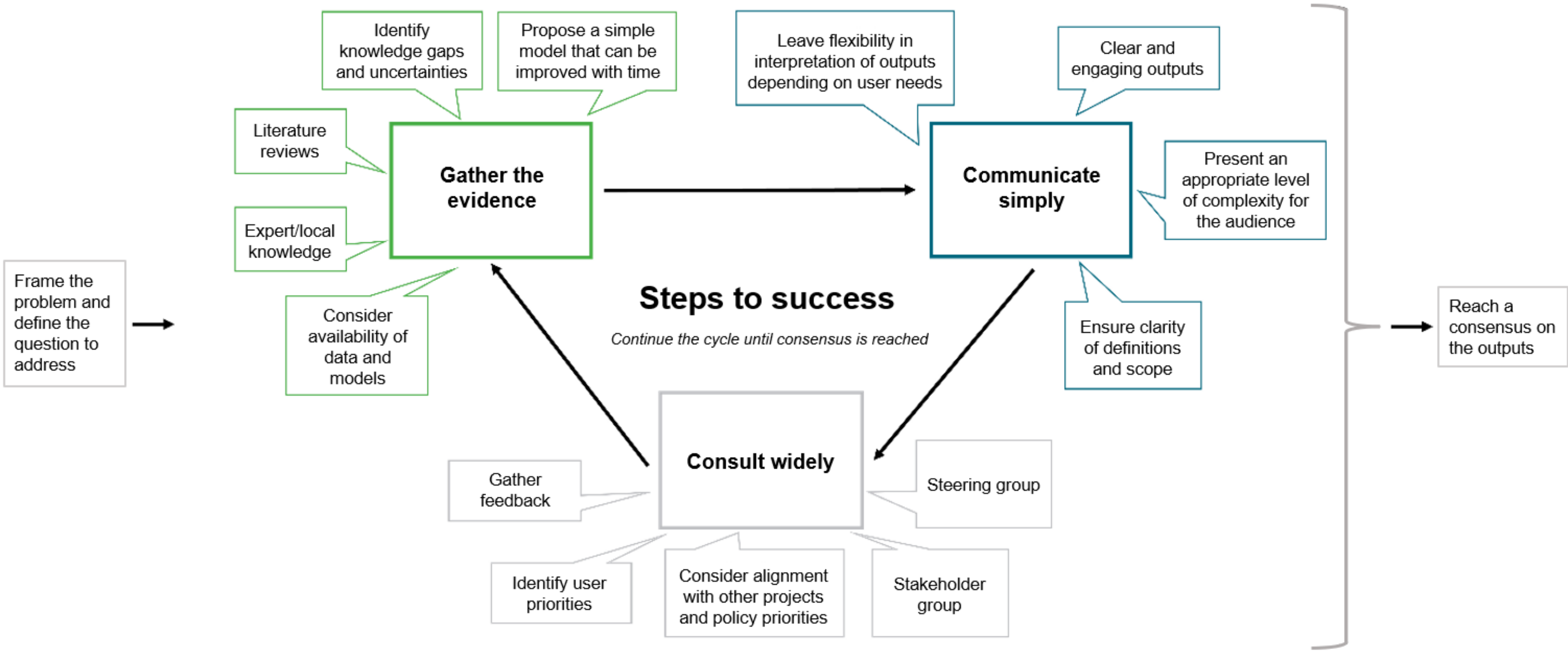

Figure 4. Steps to success. A graphical representation of lessons learnt from previous projects developing indicators of complex systems which are transferable to future projects. The key conclusion was that an iterative approach is essential. The current proof-of-concept study would represent the first 'loop' of the diagram, with further "loops" and improvements needed before the creation of indicators that can be applied and used with confidence.

4 The proof-of-concept

This section outlines the proof-of-concept project undertaken with limited resource to provide a justifiable and practical approach of developing a soil health indicator, that could be used in subsequent engagement with policy, users on the ground and soil specialists to gauge stakeholder acceptability. The outputs presented in this report are by no means the final version, but rather demonstrate a mechanism by which a set of soil health indicators could be developed. It is recognised that significant further work and additional resource are required to improve the outputs to the extent where the set of soil health indicators could be fully functional.

The general approach taken within the proof-of-concept is outlined in Figure 5. The study first identified soil properties from the scientific literature that are related to soil functions that have been associated with the delivery of ecosystem goods and services (Section 4.1 and Annex 1). Salient soil properties were then brought together using expert knowledge to create a conceptual model of factors affecting the delivery of each of the four selected ecosystem services (Section 4.2 and Annex 3). For two of these four services, statistical probability modelling was used to create a framework into which data could be entered and the expected level of contribution to ecosystem service delivery (high, medium, or low) could be estimated (Section 4.3 and Annex 3). This information was presented on an interactive dashboard (Section 4.4) and is expected to be interpreted alongside additional information from the field (Section 4.5). Each of these steps is outlined in further detail in the following five subsections, and further technical detail is provided in Annexes 1 to 3.

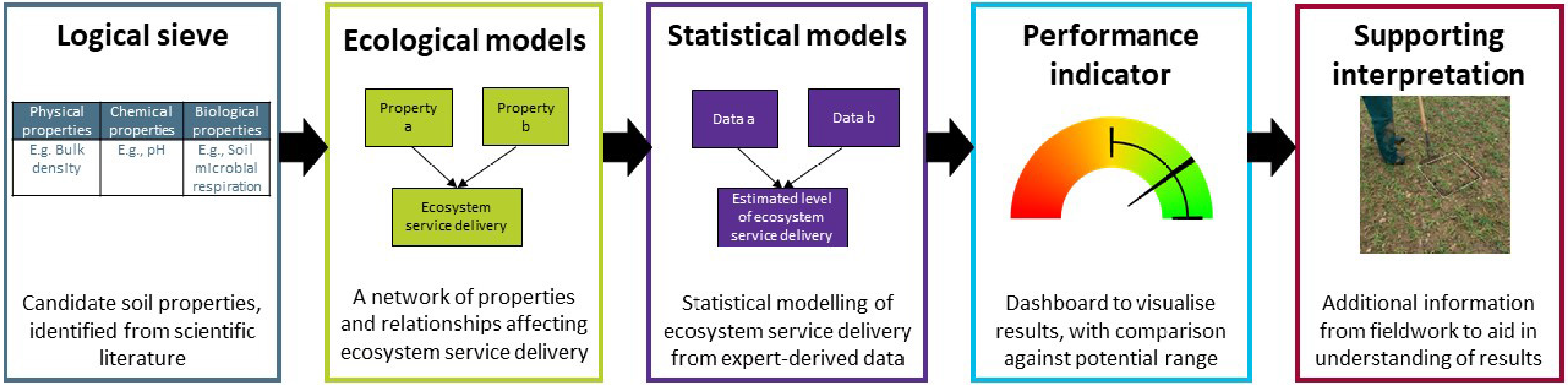

Figure 5. The general approach taken within the proof-of-concept to develop soil health indicators.

4.1 Identifying candidate soil properties (Logical sieve)

The first step in the approach was to identify which soil properties could be used to measure and monitor meaningful changes in soil health in England. (Here, a 'meaningful' change in soil health is considered to be when there is an associated change in both soil function and associated delivery of ecosystem goods and services).

This was done by performing a semi-systematic literature review of soil properties that have previously been used within the scientific and grey literature to represent soil health or aspects of soil health. The strengths and weaknesses of these candidate soil properties were evaluated against a set of criteria developed to identify the most appropriate soil properties for the current project.

The evaluation of the candidate soil properties was based on an approach developed by Ritz *et al.* (2009), known as a 'logical sieve', which originally aimed to act as an objective and quantitative means of ranking different soil biological properties as indicators of soil health. The logical sieve is a formalised method for assessing the relative strengths, weaknesses, and suitability of different soil properties as indicators of soil health. The current project based its assessment criteria on a subset of those developed by and used in Rickson *et al.* (2012), including a scoring for each soil property (i.e. 'challenge criteria', see Annex 1 for the full list) as to:

a) how well it linked to the delivery of ecosystem services,
b) its relevance across all land use types,
c) its policy relevance,
d) its measurability,
e) the availability of data; and
f) a number of other relevant factors

When selecting soil properties that can be fed into models of ecosystem service delivery, how both dynamic and static soil properties determine soil health were noted. 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 in a given location but may constrain the ecosystem service delivery that is possible within that location. An example would be soil texture affecting infiltration of rainfall and ultimately, the soils' ability to contribute to the delivery of water regulation. Whilst soil texture is useful to set the context of ecosystem service delivery, it was not included in the candidate list of indicators of soil health. This is because this soil property is unlikely to change over time and as such, repeated measurements of soil texture will not detect changes in soil health.

A total of 48 soil properties associated with soil health were identified from the reviewed literature. Following scoring and ranking in the logical sieve, the top 25% (Table 1) were carried forward to the next phase of the project (i.e. used as inputs to the ecological modelling of soil properties affecting soil functions and their contributions to the delivery of different ecosystem goods and services). Details are given in Annex 1.

Table 1. Top scoring / ranking of soil properties associated with soil health from the literature review.

Logical sieve score rank (top 25%)	Soil property
1	Soil organic matter / soil carbon
2	Bulk density / porosity
3	pH
4	Infiltration/hydraulic conductivity
5	Water holding capacity
6	Soil nitrogen
7	Soil respiration
8	Aggregate stability
9	Microbial/fungal diversity
10	Soil structure + aggregate distribution
11	Earthworms
12	Microbial biomass carbon

A key advantage of the logical sieve approach is that it is a repeatable process. It not only provides a current view of the state of soil properties that can be measured and included in attempts to understand soil health, but it can also be re-run to improve the 'score' or 'ranking' of other soil properties that may become more quantifiable due to the future introduction of novel measurement technologies, for example. The logical sieve can also be adapted over time and is flexible to accommodate the agenda of a range of stakeholders. For example, new challenge criteria can be added as they arise, or different weightings given to the different components of the sieve to reflect changes to current drivers (e.g. policy relevance). This means the approach allows an up-to-date evaluation of soil properties beyond the present point in time of this proof-of-concept study.

For further detail on the methods used within the literature review and logical sieve approach, see Annex 1.

4.2 Developing a network of properties affecting ecosystem service delivery (ecological models)

The next step was the development of conceptual models representing how different soil properties (selected from the logical sieve approach and expert knowledge) affect the delivery of four key ecosystem services. The four ecosystem services selected were: climate regulation (through soil carbon storage); water regulation (through soils' contribution to runoff reduction); maintenance of biodiversity (through soil biodiversity); and food and fibre production potential (through soils' contribution to land capability for agriculture). This is because a) these ecosystem services reflect headline goals in the 25 Year Environment Plan (where soil has a key impact or influence) and b) they cover the diversity of services soils can deliver. Again, with additional resource beyond the proof-of-concept study, it would be possible to model other ecosystem services that are underpinned by healthy soils.

The networks are a simplified representation of reality and do not capture every possible relationship in the system. However, they do aim to capture the key relationships that would have the most significant impact on soils' contribution to the delivery of the ecosystem service in question. The conceptual models were constructed based on expert knowledge of the mechanistic and empirical processes that link environmental variables to ecological processes to the delivery of an ecosystem service. Over time, it could be possible to add more nodes to the networks as knowledge develops. It would also be expected that over time it would be possible to record a stronger evidence base behind each of the linkages within the networks, reducing reliance on expert judgement.

The networks include both factors for which there is widespread data available at a national scale, and factors for which inputs (e.g. land management decisions) from a particular location of interest would be required in the statistical modelling step. This means that it is possible to start to understand whether there is enough robust data available on the factors of importance, which could help to prioritise data gathering in (future) monitoring schemes. It also means that it is possible to start making inferences about a soil's ability to help deliver goods and services (i.e. soil health) even if you have not taken specific measurements. This is useful in terms of providing a starting point to allow initial policy and land management decisions to be taken without waiting for additional data collection, whilst providing a platform that future data collection can add to and improve.

The networks also include soil properties that can vary (such as soil organic matter as affected by land management practices and climate) and others that are inherently based on the soil type (such as soil texture). There have been many attempts to classify soils into different types based on their inherent properties. Where classification systems are relevant to the ecosystem service in question and where widely used geospatial datasets are available, it may be useful to use them to represent these inherent properties in the model. Where more than one soil classification system is relevant to an ecosystem service, it is possible to use both within the model. This also allows for potential emergent classification systems to be added in future. In this way, the project is not aligning with a single soil classification system, but rather pulling from various systems of most use to the outputs.

For the current proof of concept, only land management decisions relating to agricultural land (and subsequent effects on soil properties) are included, but with further work decisions relating to other land use types could also be included, such as soil handling practices on construction sites and their effects on soil properties, functions and the delivery of ecosystem services.

An example of one ecosystem service network developed by the current project is shown in Figure 6. Further details on the methods can be found in Annex 3.

4.3 Statistical modelling of ecosystem service delivery (statistical models)

For this proof-of-concept, two of the conceptual models (i.e. soils' contribution to: a) climate regulation through soil carbon storage; and b) to water regulation through runoff reduction) were translated into a statistical model, Bayesian Belief Networks (BBNs), to enable production of quantifiable outputs. BBN modelling can be used to build on a conceptual model, by adding numerical and probabilistic values. This allows for the prediction of the likely consequences of changes to inputs to the system, which can be particularly useful for applications such as predicting the likely effects of changes in land management actions and in environmental factors on ecosystem services. For example, BBNs have been applied to soils to determine soil compaction risk based on the interaction of factors such as soil type and structure, machinery, and soil wetness (Troldborg *et al.* 2013). Furthermore, the Bayesian model is flexible so can model a variety of different habitats, with different branches of the model being relevant, or not, to each individual land parcel of interest. For example, whilst earthworms may be a good biodiversity indicator for some habitats (e.g.

improved grassland, arable) they may be less pertinent in others (e.g. heathland, coniferous plantations). The Bayesian model has the ability to reflect these nuances.

The use of BBNs means it is possible to integrate different types of knowledge, including spatial data and stakeholder expertise. Whilst the ideal would be for the modelling to be based entirely on observed data, sufficient empirical data on many soil factors and the relationships between them are not currently available. The ability to make use of expert knowledge where required, without losing out on the value of the data that are available, is therefore a key part of the current proof-of-concept stage of the project. The ability to use either or both types of input will allow for improvement of the model in the future as new data and knowledge sources become available.

The current version of the modelling takes national spatial data where it is available (e.g. climatic factors, soil texture classes), allowing users to click on a location on a map to autofill relevant data. However, the current model also relies on two different types of expert input. Firstly, the app relies on the user to input local expertise about soil properties for which spatial data is not available. This also includes inputs about agricultural management decisions (e.g. tillage, crop rotation) and factors which may be relatively obvious to a farmer or landowner but for which data is not currently available nationally (e.g. use of artificial drainage). Secondly, the relationships between nodes in the model itself are defined by expert input. At this proof-of-concept stage, this has been based on input from a relatively small number of soil experts who are part of the project team.

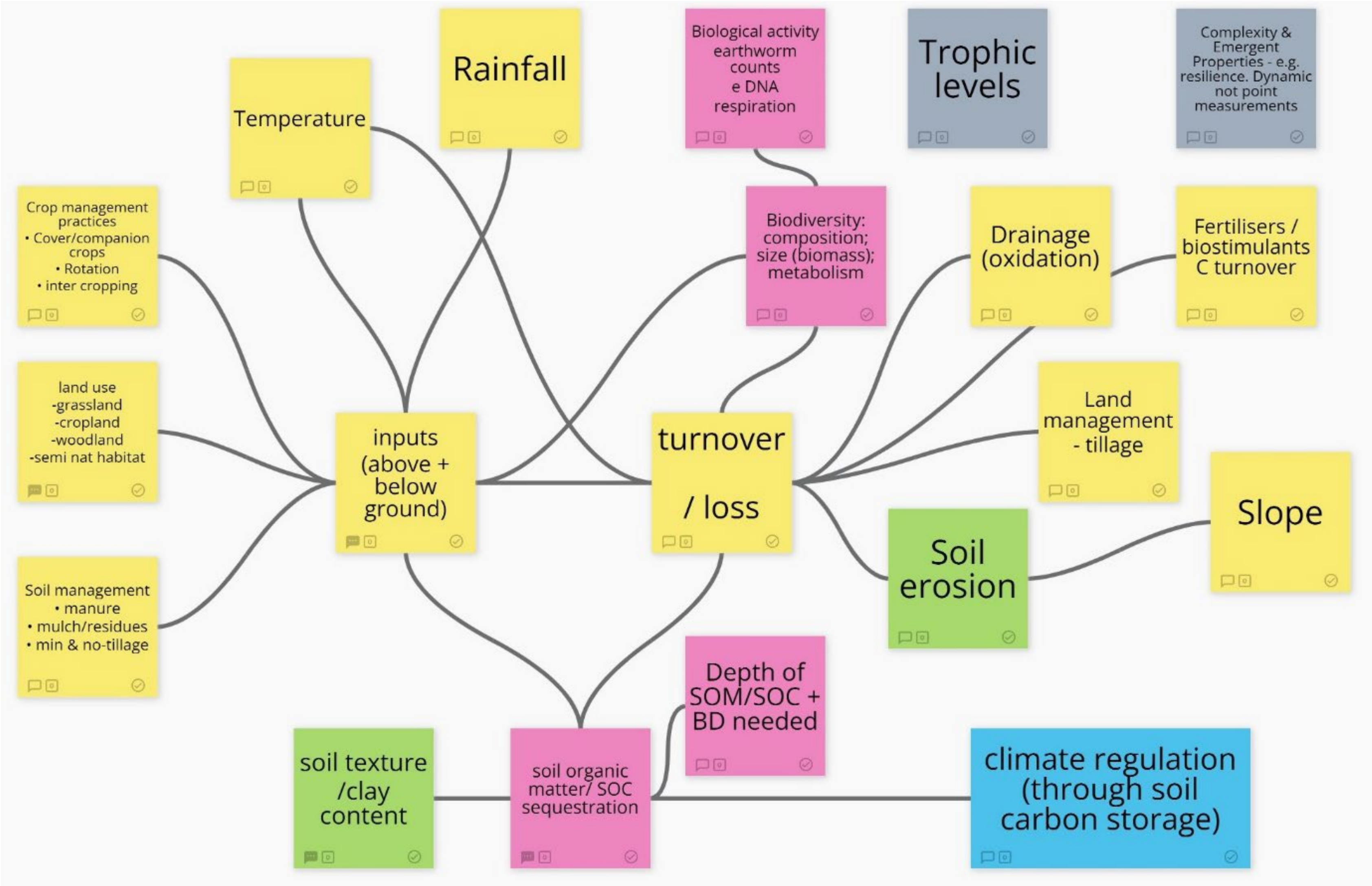

Figure 6. A conceptual ecological model showing soils' contribution to the delivery of climate regulation as an ecosystem service through soil carbon storage. The elements within the model are categorised as: environmental variable (yellow); soil property (green); soil property identified from the logical sieve (Table1) (pink); Ecosystem Service outcome indicator (blue); other consideration (grey).

Consequently, the model currently makes a best prediction based on the information available and may not reflect site nuances. In subsequent iterations, it will be important to obtain feedback and input from a wider range of experts in order to improve confidence in the modelling. This would need to follow a more structured and accepted process for gathering expert input, such as those recommended in JNCC's EQA guidance (including the Delphi method and advice collated in a JNCC report by Barnard and Boyes (2013)). It would likely be possible to achieve an adequate level of assurance within an additional 1 to 2 years of project work. Ultimately, if data were available for all inputs (which would likely take several years of directed effort), it would be possible to define these relationships numerically as part of the modelling, rather than rely on expert input. This would fundamentally change and ideally improve the modelling approach but would not change the concept.

The reliance on site-specific input makes the approach particularly useful and flexible locally, but constrains current use at a larger scale, highlighting the data improvements that would be needed when developing the proof-of-concept to a fully functional set of indicators. Integration of national scale soil monitoring schemes in future iterations would be necessary to overcome this, and meanwhile appropriate communication around this gap is important, potentially promoting particular parameters at this scale that would make such an application (e.g. larger scale indication) operational. Incorporation and integration of national schemes and local site measurements into the model in future iterations will help reflect specific site nuances.

Soil properties highlighted in the literature review stage (see Annex 1), but for which there is no data and no easy way for a local user to input their own data were excluded from the modelling at this proof-of-concept stage. Again, further development following monitoring schemes and an improved data landscape could give scope to add these factors in the future.

At the current stage, the outputs of the modelling provide an estimate of the probability that delivery towards a given ecosystem service (as represented by soils' contribution) is 'high,' 'medium,' or 'low' based on the inputs given and an expert judgement of what constitutes 'high,' 'medium' and 'low'. Again, if it became possible to base the entire model on data rather than rely on expert knowledge to define the relationships between nodes, it would be possible to produce a numerical rather than a categorical output.

Time constraints meant that it was not possible to model the networks for a) the maintenance of biodiversity (through soil biodiversity); or b) food and fibre production potential (through soils' contribution to land capability for agriculture). However, the preparatory work to make this a straightforward task in the future has been undertaken through production of the initial, underlying conceptual models (see Annex 3).

4.4 Visualising results (performance indicator)

The concept proposed for visualising results of the project was described in Section 3.1, consisting of a set of dials that estimate both the ecosystem service delivery and the range of possible delivery based on the inputs selected. However, with the limited level of data and information available within the constraints of this short proof-of-concept study, it was not possible to present results in this way. This is because that would require a numerical output, rather than estimates of the probability that delivery is 'high,' 'medium,' or 'low,' based on conditional probability tables derived from expert judgement.

Instead, data in the current version are presented as a series of concentric pie charts. Each ring is composed of three segments, which represent the probability that the soils' contribution to ecosystem service delivery (given the particular combination of inputs selected) is: 1) low, 2) medium or 3) high. Therefore, the higher the probability of ecosystem service delivery, the larger the green segment will appear. There are three rings in each chart. The inner ring represents the average across all land parcels within the UK. The middle ring represents the average for all land parcels of the same land use and soil type as the land parcel selected. The outer ring represents the specific land parcel selected on the map, reacting to input from radio buttons on land management decisions taken (Figure 7). In order to get back to the vision presented in the previous section, it would be necessary to obtain data for all model inputs and model the relationships between them, rather than relying on expert inputs to define the relationships. In the meantime, however, the current presentation provides a useful start on which further iterations and improvements can be made. For the purposes of a particular indicator (especially at an early stage where the aim is to prove the concept rather than create a finalised indicator), it is not critical that any given measurement is estimated with 100% accuracy. Rather, the important part is understanding if a particular land parcel (including its soils) is contributing more or less to an ecosystem service relative to others of a comparable nature, and how to improve it. The current visualisation (Figure 7) meets this objective, even though it is fairly rudimental compared to the ultimate vision.

4.5 Gathering additional information from the field (supporting interpretation)

Gathering extra data will be an essential part to interpreting and improving the set of soil health indicators produced in this proof-of-concept study.

An indicator will only ever be indicative of true state. Taking additional measurements in the field can help to confirm results from the indicator and support its interpretation. For example, the model may predict only one outcome for a land parcel, but variability within that land parcel may give very different soil properties (and thus indicator results) when measured in the field.

Further data can also help with validation and calibration of the modelling behind the given indicator. To reach a usable stage, the indicator would need to go through a ground-truthing process where model predictions of soils' contribution to ecosystem service delivery are compared with evidence on the ground, in order to understand the accuracy behind the model and confirm that it produces a reasonable proxy of reality.

As previously mentioned, additional data sources from future monitoring programmes could also be used as inputs for the model itself (both in terms of soil properties and evidence of the relationships within the model), thereby improving the accuracy and reliability of the model outputs. Therefore, the production of a predictive indicator does not reduce the need for monitoring in the field.

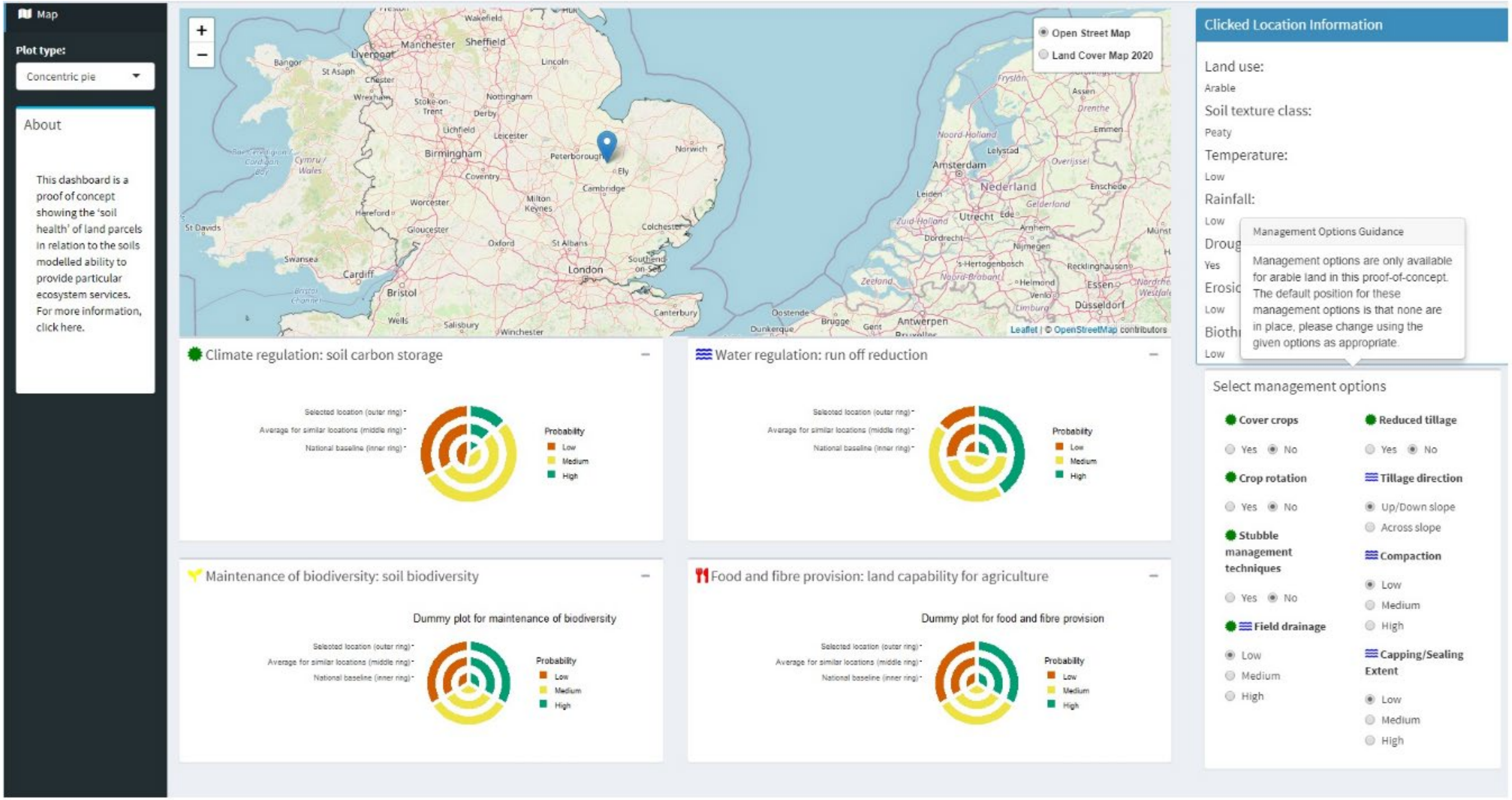

Figure 7. A screenshot of the dashboard produced to present the results of the current proof-of-concept. The explanatory pop-up activated by clicking in the 'About' section gives an overview of the app, its uses and potential future developments.

5 Stakeholder engagement and future application

As a final step in this proof of concept project, and in keeping with the communication and collaboration 'steps to success' illustrated in Figure 4, a series of meetings were held with key stakeholders (Forest Research, Natural England, Environment Agency) with links to soil monitoring (England Ecosystem Survey, NFI+ and Soil Structure Survey), to communicate the indicator concept, seek feedback and explore how the set of indicators could be used in practice.

These meetings and the preparation involved resulted in a series of high-level case studies of how the indicators could be used (Section 5.1), feedback on the indicator concept (Section 5.2) including useful comments on and challenges to the concept (and/or its communication), and a concise presentation of the concept (available on request). High level case studies to detail opportunities on how the set of indicators could be used were discussed and insights to consider for the future stage of turning the concept into reality were gathered.

5.1 How the set of indicators could be used

Potential uses for the proposed soil indicator framework can be categorised according to the purpose of use (e.g. describing current status or predicting status in future scenarios; or the scale of use (local to national)). Further specific indicator developments and considerations would be needed to make them suitable for the different combinations of applications, as set out below. Some example specific use cases are set out in Table 2.

For all uses, it is a given that the models behind the indicators would have to be developed to be based on more data (particularly data from soil monitoring), and the relationships between model nodes should be refined to be focused on data as opposed to the current reliance on expert opinion.

5.1.1 Describing current soil status in relation to ecosystem services

Local scale

- The app is currently designed to describe best estimates of soil status at a local level, primarily based on national datasets.
- Facilitating the entry of local data and knowledge would improve the estimates.
- Currently the app has the ability to select land management options. This is used to estimate if the current local soil health status could be changed via implementing different land management options.
- The intention would be to add a mechanism for users to directly input local soil measurements. This would likely lead to more accurate local results than current outputs based on national datasets or land management options, so if this local data were incorporated it would need to take precedence (as appropriate) over other data types in the model.

Regional/National scale

- The app currently displays results at a local level (based on an underlying 25 m data grid) and compares this to the national average and average of similar types of site. It would be useful to develop the app to display average results at other large scales (e.g. country and regional levels).
- This could include pre-set regions or land areas (e.g. all protected sites), but for

maximum usefulness, it would have the option to define the boundaries of the region of interest, or to select the user's own collection of land parcels of interest (e.g. if a large landowning organisation wanted to see average soil health across all their landholdings).

- If the app were used at this broad spatial scale, it would not be feasible to make use of bespoke, site-based data on soil properties or land management to refine estimates of status. In any case, this would be less important when considering large spatial scale averages. It would also require guidance on summarising across soil or land-use types, avoiding one or both if possible.

5.1.2 Predicting impacts of land management decisions

Local scale

- The app currently has the mechanism to toggle on and off land management options, so the app can be used to display the estimated soil health status with or without the different options to aid land management decisions. The default land management includes a 'conventional' farming option. Other land management options include cover cropping and minimum tillage.
- Careful communication would be needed around this, noting that the effect of land management on soil properties as presented is not site specific: it is just a typical level of improvement in soil health status if a particular land management option is applied, and it may require several years of applying this option to reach this level of benefit.
- If the mechanism to indicate the effect of land management options was used in combination with actual site soil data, the app would need to be flexible depending on whether the user was intending to use the app in a descriptive or predictive capacity (i.e. in the descriptive capacity, any actual site data would take precedence in the model, but in the predictive capacity, it would make sense for the selection of land management options to indicate potential improvements to status).

Regional/National scale

- The models and app do not currently have the ability to predict soil status for scenarios at large spatial scales, but it remains an aspiration for how they could be used in the future, for example to investigate the potential impact of introducing a particular agri-environment scheme. The outputs could inform the design of the scheme.
- The current indicator model and/or the app would need further development to predict the outcomes of land management decisions. This could include allowing the land management options 'on/off toggles' on the dashboard to apply to wider regions (pre-set or self-selected) or collections of land parcels of interest. Of course, it is unlikely that a land management option would be either completely 'on' or 'off' when considering a large area of land. It may therefore be useful to introduce a slider of % uptake of particular land management options when using the app for predicting impacts at this spatial scale.
- Another feature that would be useful for large scale decision making (albeit potentially challenging to implement simply) would be a mechanism to predict the impact on soil health of changing the land use of an area. This would also be most useful as a continuous rather than binary variable, for example to gauge the impact on soil health of a gradually increasing proportion of forest cover across a region.

Table 2. Example use cases for the set of soil health indicators.

User	Requirement	How it could be used	Challenges/further developments
Individual landowners	Understanding of status of their land and how to manage their land to meet their needs in an environmentally friendly way. Potentially this could be linked to participation in agri-environment schemes, either to demonstrate their land is meeting a particular standard (e.g. SFI), or as an agri-environment scheme endorsed tool to help guide action. Alternatively, it may be most appropriate in an advisory function. Switching land management options off and on, to see the likely effect on soil from enacting certain schemes to make informed choices.	They would select appropriate land management options and take relevant soil measurements from their land where possible as inputs into the models. This could be combined with data from national datasets, resulting in indicator outputs for their land.	Guidance would need to be produced on how to use and interpret outputs. Caution is needed in judging how appropriate it would be to link results into agri-environment funding decisions (e.g. consideration needed on risk of falsification of local data inputs, appropriate tolerance of level of uncertainty for this use case, and whether it would be better to link payments either to action taken or by results). Third-party verification or spot-checks, combined with automated processes such as remote identification through satellite imagery, could be explored to mitigate such a risk. For example, there are a number of developments in machine learning and remote sensing techniques to estimate soil quality indicators (e.g. Diaz-Gonzalez *et al.* 2022). If used as an advisory tool, it must be made clear that the model will only estimate the outcomes of different land management options and be clear about levels of uncertainty.

User	Requirement	How it could be used	Challenges/further developments
Landholding organisations, e.g. Forestry Commission, National Trust, Wildlife Trusts, Crown Estate	Understanding status of soil health across their land holdings. To guide decision making for land management across their land holdings.	The app could be used on a descriptive basis and to predict the impacts of land management options across land holdings. Whilst it would not be possible for users to manually add bespoke site data when considering large areas with multiple sites, large scale datasets from across land holdings (e.g. soil data from NFI+) could be incorporated in the indicator models.	This use case would require some of the model developments for regional/ national scale as described above (e.g. ability to select land areas of interest, and introduce land management options as continuous (e.g. % land affected) rather than binary variables).
Governments/ Statutory Nature Conservation Bodies (SNCBs)	Understanding/reporting overall status of soil health at UK, country or regional level. Considering trade-offs in soil health in relation to different ecosystem services and when to help inform environmental policy and land use decisions.	The set of indicators could be updated on an annual basis for overall understanding and reporting purposes (though noting not all model input data would be updated as frequently). Adjusting options for land use and land management would help with predicting impacts of different policies as they are being designed.	We do not have one 'overall soil health' indicator – soil heath in relation to different ecosystem services would need to be considered together and prioritised appropriately in decision making. This fact must be clearly communicated. This should align with reporting cycles of large-scale data collection such that updates are meaningful. The models would require sufficient, regularly updated soil monitoring data to be robust for use as a reporting tool to show progress over time. (There needs to be consideration as to whether current and planned monitoring (e.g. the EES) is sufficient). This use case would require some of the model developments for predictive use at regional/national scale as described above.

5.2 Summary of feedback on indicator concept from initial stakeholder consultation

Overall feedback on the proof of concept was positive and stakeholders could see its potential, though more development would be needed to make the proof of concept operational.

Development is primarily needed in terms of strengthening the underlying statistical models to incorporate more data inputs and enable quantitative indicator outputs that could be presented using the originally envisaged ‘speedometer type’ display. This depends on sufficient data being available to make the models adequately robust. The data easily available for use in this proof of concept were limited, though it is noted that new monitoring schemes currently being planned or piloted (e.g. EES, NFI+) could help provide this, if they collect the relevant parameters at an adequate spatial and temporal scale, and range of sites. Further data (alongside soils expertise) are also needed to strengthen the robustness of relationships between nodes in the statistical model. An important feedback point received was that the models need to further consider nuances between habitat types, for example, a variable such as ‘earthworm density’ could be a positive indicator of soil health in one habitat type, but less relevant in another. A Bayesian Belief Framework is flexible enough to deal with this, but further evidence-based development and QA of the conceptual and statistical models is vital to ensure outcomes are robust and trustworthy.

Another piece of feedback was a recommendation to review the land use classification system, and the soil texture inputs (i.e. for specificity) used in the process, leading to optimal options being put forward to users. In the absence of soil texture data at the resolution needed by the user (e.g. field scale), this could be estimated in the field by the user following a simple hand texturing technique to ascertain soil texture (e.g. https://ahdb.org.uk/knowledge-library/soil-assessments/determine-soil-texture). This review would involve scoping the needs of end users and providing clarity on what different choice land us classification systems would provide (e.g. in terms of accuracy).

The current proof of concept focussed on soil health in relation to a limited number of ecosystem services. The intention is to have indicators for a wide range of ecosystem services that could be viewed in parallel. This multi-indicator concept was well received, and the series of ‘speedometer’ type displays considered to be a clear approach to communication. A suggestion was received that it may be useful if the display showed the distribution of soil statuses of other sites alongside where a site fits within a basic range. This could be achieved by turning the black range line on the dial into a histogram/kite diagram to show the distribution. Further consideration of this is needed. Whilst displaying extra information could be useful, it may detract from the simplicity of the indicator display. There is also consideration needed on how this additional context might influence the motivation of land managers using the product (i.e. if most other similar sites are in poor status, motivation for trying to improve a site might be lost).

When considering how the set of indicators could be used in practice, it became clear how many requirements the concept is currently trying to meet. Therefore, when transforming the concept into a functioning product, initial focus should be on refining the soil health status description side of the model. The predictive scenario testing side of the app should be ‘phase two’. To keep it simple, it may be more appropriate to develop the predictive scenario testing as a separate app, or at least be able to switch the existing app between descriptive and predictive modes. There will need to be some tweaks to the underlying statistical model depending on the intended application.

Further developments need to be made to the app for both the descriptive and predictive uses. For the descriptive use this includes expanding existing parts (e.g. by increasing the range of land management options and the range of land use types that are available). For use at different spatial scales and scenario prediction, substantial developments would make the product more useful, including the ability to select larger regions of interest (as opposed to just individual points); the ability to consider uptake of land management options as a continuous rather than binary variable; and a mechanism to explore how changes in land use as well as land management could impact soil health status in relation to delivery of ecosystem services.

6 Conclusions

In conclusion, this set of draft soil health indicators provides a proof-of-concept (Figure 5) which is working towards the overall requirements for an indicator of soil health, using available spatial data and expert knowledge to map out conceptually the pathway to soils' delivery of ecosystem services (Figure 6). The study has demonstrated how it would be possible to communicate the effectiveness with which soils deliver these services under differing inherent properties, land use and land management choices (Figure 7). We provided tools that systematically evaluate salient soil properties for inclusion in models that as a result, will be relevant and useable (Table 1). We have developed demonstration ecological and statistical models which we present through a pilot version of an app to present outputs as a set of soil health indicators. We have focused on immediate useability, adaptability and improvability to meet current and future requirements in our approach (Figure 4). Currently we have achieved this for agricultural soils at the land parcel scale, comparative to the national average.

This is the first iteration of an ongoing process. The project itself was a proof-of-concept, and as such it is the approach that is being developed and tested, rather than the final outputs themselves at this stage. These should not yet be seen as usable indicators. In light of the complexity demonstrated through this proof of concept, and the potential extensiveness of developments that could be useful to implement, it is recommended that a cost-benefit analysis is carried out before further development is initiated. This would involve fuller consideration of the data sets available. This should be carried out in parallel with further understanding of the required development of ecological and statistical models, reviewing costs, efforts and compatibility as appropriate. The cost-benefit analysis would need to include further stakeholder consultation and include broadening the stakeholder groups to enable a judgement to be made on the level of accuracy and robustness required of the indicators to be considered adequate for different uses.

Once a full understanding of requirements, their costs and the benefits of prioritising certain aspects are explored, further key next steps can be taken. For example, a more extensive and systematic process for obtaining expert input to improve the probabilities associated with the modelling (BBN) should happen for all elements (e.g. nodes, ecosystem services, etc. taken forward). The benefit of this step is that whatever elements are priorities, if appropriate expert knowledge is used, it will be useable before data is available on all nodes within the model (to enable a numerical approach). Whilst the aspiration is that the end state is totally data driven, the flexibility allowed by this proposed approach provides a necessary, yet still sufficient alternative.

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Glossary

Table 3. Glossary of terms used within the report.

Word	Definition in the context of this report	Commentary
Attribute	A property or a characteristic of soil, ideally that can be measured and quantified.	Used interchangeably with ‘property’ and ‘measurement’.
Climate regulation	The ability to act as a net sink for GHG, for example through sequestration and storage of carbon, and prevention of carbon losses to the atmosphere. In the context of this project, focus is only on carbon sequestration within soils.	Example for CO_2: Soils are able to sequester CO_2 from the atmosphere through photosynthesis; store carbon through soil organic matter content and prevent C losses through soil erosion control. N.B. Soils can be sources of CO_2 too through drainage of peats, inversion tillage and soil erosion for example. This project currently only considers CO_2 – future iterations of the indicator could include additional GHGs such as methane.
Conceptual framework/ conceptual ecological model	Presentation of a series of relationships between data and/or variables.	The level of detail describing the relationships can vary, as can the level of input data that are associated with the framework.
Ecosystem services	“The contributions that ecosystems make to human well-being and arise from the interaction of biotic and abiotic processes” (Haines-Young 2010).	Under the MEA, services are typically divided into ‘provisioning’, ‘regulating’, ‘supporting’ and ‘cultural’ services. Note: “The capacity to deliver a service exists independently of whether anyone wants or needs that service… that capacity only becomes a service if some beneficiary can be clearly identified” (Haines-Young 2010). The project uses proxies (properties with a proven relationship to soil health based on the literature review presented in Annex 1) to represent each of the four ecosystem services, (e.g. climate regulation is currently based on carbon storage rather than regulation of all GHGs).
Food and fibre production potential	Soils’ contribution to land capability for agriculture and ability to support food and fibre production.	

Word	Definition in the context of this report	Commentary
Function	Something specific that is achieved. For example, one function of soil is to filter water.	Note, the specific thing achieved could be delivery of a soil function, ecosystem good or service.
Index / Indices	A number that indicates something. Can be based on processing and combining multiple data inputs.	The term indicator is preferentially used in this project.
Indicator	"A measure based on verifiable data that conveys information about more than just itself. This means that indicators are purpose dependent - the interpretation or meaning given to the data depends on the purpose or issue of concern" (Biodiversity Indicators Partnership, n.d.).	
Land cover	The physical type of cover in a certain land use	For example forest, bare ground, grassland, urban
Land management	The methods used to manage the land under various land uses	For example intercropping, cover cropping, crop rotation in arable land
Land use	How the land is used for different purposes.	For example plantation forest, natural forest, pasture, semi natural grassland, residential
Logical sieve	A formalised method for assessing the relative strengths, weaknesses, and suitability of different candidate measurements of soil health	
Measurement	A quantified soil attribute, property, or characteristic	Used interchangeably with 'attribute', and 'property'
Metric	"A system for measuring something" (Cambridge Dictionary 2022). In the context of soils, a metric would be the way a soil property is measured / quantified.	The term 'measure' should be avoided as it is ambiguous in that it could relate to soil management measures in the field.

Word	Definition in the context of this report	Commentary
Natural capital	The total value of soil to perform ecosystem services (linked to soils quantity, quality, and other relevant spatial factors such as accessibility to make use of a service).	The natural world equivalent of having money in a bank account. “At its simplest, a natural capital approach is about thinking of nature as an asset, or set of assets, which benefit people. The ability of natural assets to provide goods and services is determined by their quality, quantity, and location. These in turn can be affected by background pressures, management practices and drivers of demand” (Defra 2021).
Parameter	“Any of a set of physical properties whose values determine the characteristics or behaviour of something” (Merriam-Webster Dictionary n.d.).	Note – parameter also has specific other definitions associated with certain fields, for example when used in the context of statistics, it can mean “a quantity (such as a mean or variance) that describes a statistical population”, where data has been taken from the whole population and not just a sample. However, the context in which it is used in the report is that defined here.
Property	A characteristic of soil, ideally that can be measured and quantified.	Used interchangeably with ‘attribute’ and ‘measurement’.
Soil biodiversity	“The variation in soil life, from genes to communities, and the ecological complexes of which they are part, that is from soil micro-habitats to landscapes” (European Commission 2010, in line with the CBD's definition of biodiversity).	

Word	Definition in the context of this report	Commentary
Soil health	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.	When speaking in general terms, this considers the range of functions that one wants a soil to perform. However, if qualified, it can be used in a specific context, for example the health of a soil to perform the functions that underpin the production of crops (provisioning service). These functions include nutrient and water retention, and availability to the crop.
Soil quality	The ability of soil to perform its functions and 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.	For the purposes of this report, soil quality is used interchangeably with soil health, although 'soil quality' can be used to refer to a specific function or ecosystem good / service, as well as in the more all-encompassing sense (i.e. all functions, and goods and services) in which 'soil health' is generally used.
Variable	"A number, amount, or situation that can change and affect something in different ways" (Cambridge Dictionary 2022).	For example, in the climate regulation network in this project, erosion and temperature are examples of variables that can change depending on the land parcel being analysed, which both affect the delivery of climate regulation as a soil ecosystem service.
Water regulation	Control of excess water (flooding) and deficit of water (drought) in the environment	Healthy soils are able to 'receive, retain and release' water to reduce flood and drought risks.

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