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Soil structure and its benefits

An evidence synthesis

SUMMARY

THE
ROYAL
SOCIETY

Overview

Focus of the synthesis

This report synthesises the evidence on the relationship between soil structure and the benefits it provides. It also examines the measurements of soil structure that land managers and scientists can use, and the interventions available to improve soil structure and prevent degradation.

Soil structure was chosen due to its relationship with water and gas permeability and the beneficial outcomes that this permeability supports.

Soil structure is also a property of the soil which can be measured and potentially rewarded as part of any new payment scheme emerging from a new agricultural policy framework.

Providing the evidence pathway between soil management, soil structure, and the benefits that good soil structure provides therefore has current policy relevance to all four UK nations, as we move away from the Common Agricultural Policy.

There are various benefits that good soil structure can help deliver. For this report, the focus will be on four benefits where there is sufficient evidence to draw upon: biodiversity, agricultural productivity, clean water and flood prevention and climate change mitigation.


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Introduction

Soil and soil structure

Soil forms the uppermost layer of the Earth's crust, consisting of a mixture of organic matter, minerals, gases and water.

Soil typically develops in layers (also known as horizons) which are distinct from one another in colour and texture (Figure 1).

We refer to soil structure as the arrangement of solids (organic matter and mineral ions) and pore spaces within soil.

For soil used in agriculture, a 'well-structured soil' will have a continuous network of pore spaces to allow drainage of water, free movement of air and unrestricted development of roots[1].

The three main types of soil particle are clay, sand and silt. The combination of these three particles determines the soil type (Figure 2). Soil type and structure have important ramifications for how soil behaves under different weather conditions and land management regimes.

FIGURE 1

A mineral soil profile.

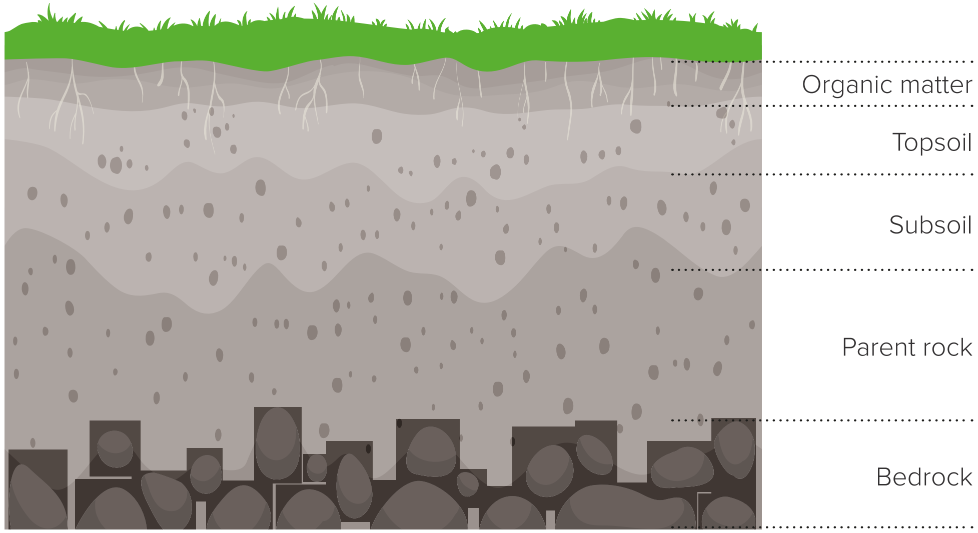
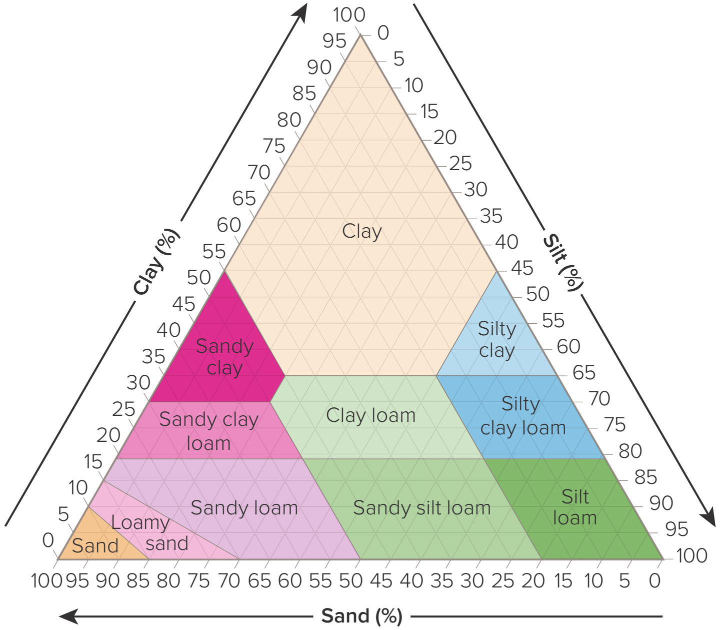


FIGURE 2

Soil texture triangle, showing the different soil types and combinations of clay, sand and silt particles[2].



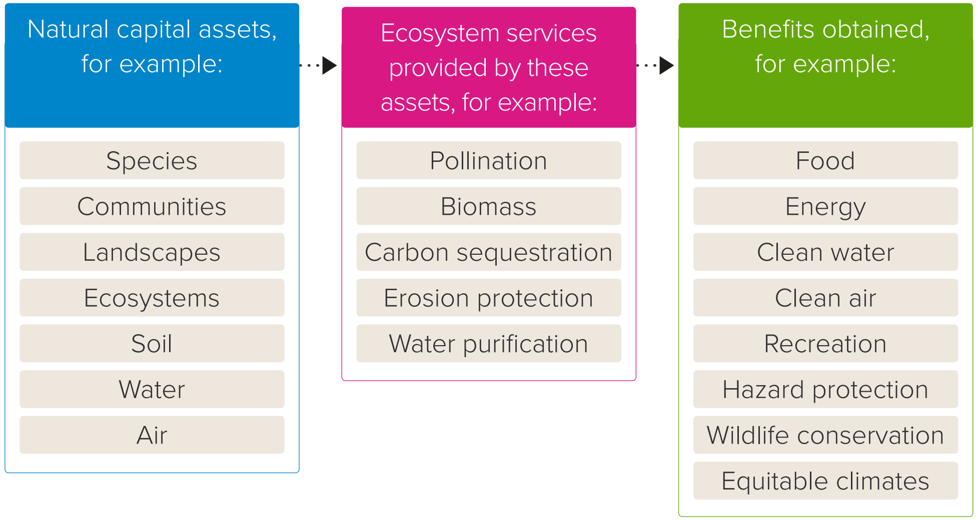
Soil structure and its benefits

As a natural capital asset, soil can be managed to generate goods and services. In conjunction with other inputs such as human labour, these goods and services generate societal benefits (Figure 3).

There is a growing awareness of these benefits and the role of good soil management in delivering them. For example, concerns have recently been raised regarding the continued ability of soil to support food production for a growing human population.

FIGURE 3

Flow of natural capital assets, ecosystem services and the benefits that can be obtained[3].



BOX 1

Natural capital assets, ecosystem services and ecosystem benefits[4]

Natural capital assets

The elements of nature that directly or indirectly produce value to people. Individual assets include ecological communities, species, soil, land, freshwaters, minerals, sub-soil resources, oceans, the atmosphere, and the natural processes that underpin their functioning.

Ecosystem services

Functions carried out by the natural environment (eg pollination, carbon sequestration) from nature that can be turned into benefits (eg food, hazard protection) when combined with human input (eg labour, machinery).

Benefits

Changes in human welfare (or wellbeing) that result from the use or consumption of goods, or from the knowledge that something exists (for example, from knowing that a rare or charismatic species exists even though an individual may never see it). Benefits can be both positive and negative (disbenefits). Examples of benefits are the aesthetic and recreational benefits of wild species diversity, food and agricultural productivity, clean water and prevention of flooding, and climate change mitigation. Benefits are the goods provided by ecosystem services.

Soil provides a large range of benefits to human society. This synthesis presents the evidence on four benefits provided by well-structured soil: biodiversity, agricultural productivity, clean water and flood prevention and climate change mitigation.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BIODIVERSITY


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AGRICULTURAL PRODUCTIVITY


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CLEAN WATER AND FLOOD PREVENTION


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CLIMATE CHANGE MITIGATION

Biodiversity

Soil structure influences the nature and activity of soil and other terrestrial organisms while soil organisms affect the physical structure of the soil and support well-functioning soil and wider terrestrial ecosystems.

Wild species diversity and abundance can be viewed as an ecosystem benefit in its own right, in terms of cultural or aesthetic value. Soil organisms also underpin several ecosystem services, such as pollination, biological pest control and soil fertility, which deliver additional benefits including food production.

Soil communities are extremely diverse, with millions of species and billions of individual organisms, ranging from microscopic bacteria, archaea and fungi, through to larger organisms, such as earthworms, ants and moles. This level of biodiversity is supported by the diverse microhabitats that well-structured soil provides.

Soil structure affects the composition of soil communities in a number of ways. For example, bacterial diversity is affected by soil particle size, with a higher percentage of larger sand particles (ie coarser soil) causing a significant increase in bacterial species richness[5].

Earthworms have an important role in maintaining and enhancing soil structure. They act as 'soil engineers' by physically burrowing in the soil and strongly influence the physical and chemical characteristics of soil layers[6].

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Agricultural productivity

It is well known that soil structure can affect crop yield. One study found there was a correlation between a good visual soil structure score and higher grain yield of cereals, with yield increases of 300 – 350 kg ha^{-1} for each unit increase in the soil structure score[7].

The physical structure of the soil also determines the likelihood of soil erosion, which can negatively affect agricultural productivity and lead to freshwater pollution. Soil erosion is the removal of the top layer of soil by water or wind. Generally, soil with higher porosity, faster infiltration rates and higher levels of organic matter is more resistant to erosion.

Arable soil typically contains 150 – 350 earthworms per m^2 and high populations (>400 earthworms per m^2) of earthworms are linked to significant benefits in crop productivity[8]. However, the tillage regimes used in agriculture can reduce earthworm populations[9].

Poorly maintained soil, for example compacted soil, is also associated with decreases in crop yield due to detrimental effects on the crop's root system. Compaction reduces water infiltration and water uptake in plants[10].

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Clean water and flood mitigation

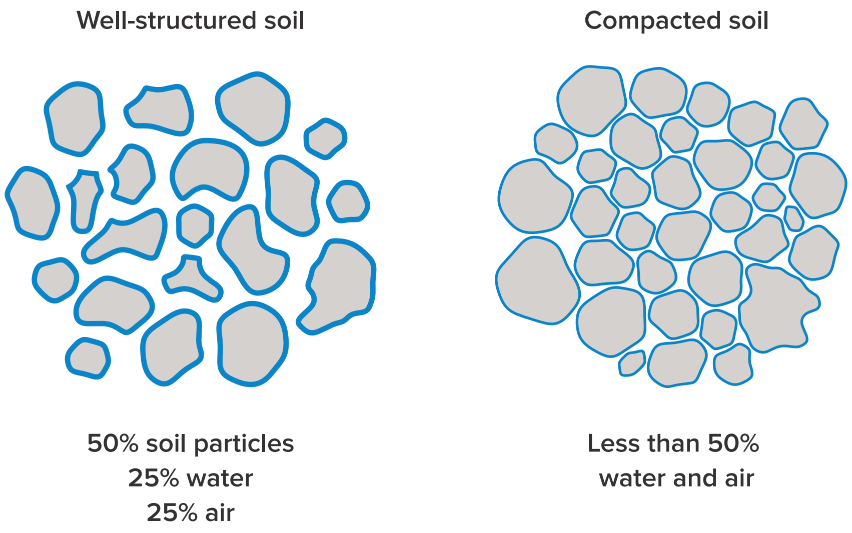
A well-structured soil filters water between the atmosphere, groundwater, lakes and rivers, improving water quality and availability. Soil can act as ‘natural flood management infrastructure’ by lowering the risk of flooding through 1) increased water infiltration into the soil and 2) providing natural storage, for example via uptake into root systems.

The water storage capacity of soil depends on the pore space between soil particles, which is determined by factors such as soil organic matter. When soil structure is degraded due to compaction, the pores are pressed together, reducing the space where air and water are normally stored (Figure 4).

Compaction significantly reduces the ability of water to vertically infiltrate the soil and thus increases surface runoff and the risk of flooding[12]. It also limits the pathways available for crop roots, affecting agricultural yields[13], and leads to greater soil erosion and the pollution of waterways[14].

FIGURE 4

Soil compaction reduces the available space for soil particles, air and water, limiting pathways for root growth[11].

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Climate change mitigation

Soil can potentially have a large role in mitigating climate change. Soil is the largest terrestrial store of organic carbon, and contains twice as much carbon as the atmosphere[15]. Soil management and the resultant soil structure can affect the carbon content of soil[16].

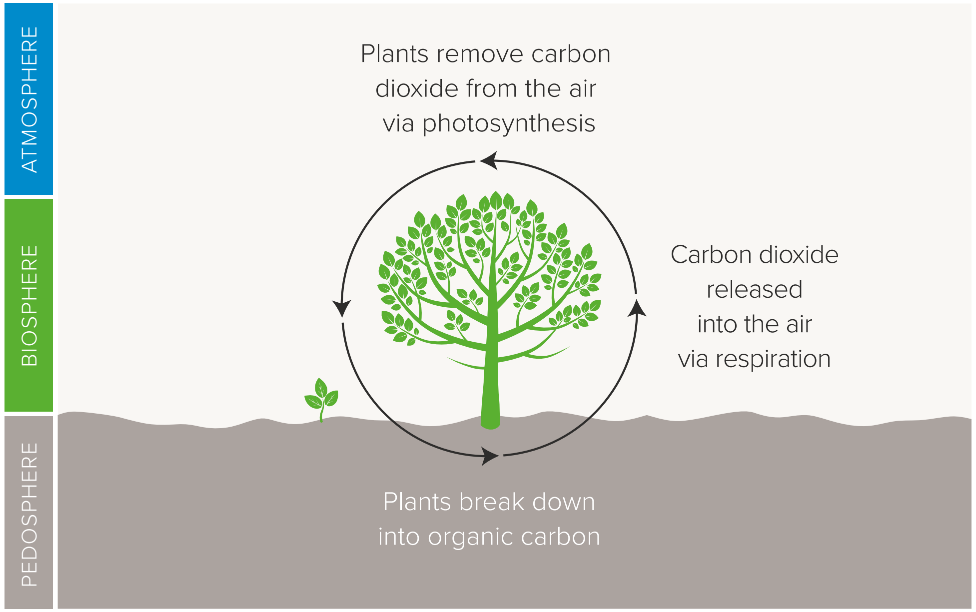
Carbon forms a significant part of total soil organic matter. Soil organic carbon levels are therefore directly related to levels of soil organic matter. Carbon enters long-term storage in soil as organic carbon from plant material and is incorporated into the soil through decomposition.

Soil carbon sequestration refers to the long-term accumulation of carbon in soil. Sequestration occurs when carbon input (for example, from leaf litter, residues, roots, or manure) exceeds carbon losses (mostly through the respiration of soil organisms, increased by soil disturbance)[17].

Land management practices affect soil structure and carbon sequestration. Practices such as reduced till and growth of soil cover crops have been shown to increase levels of soil organic carbon.

FIGURE 6

The carbon cycle.

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Measurements

There is a vast array of methods to measure soil structure with advantages and disadvantages to each.

VISUAL ASSESSMENTS

There are a variety of visual methods for assessing soil structure. These can:

- Be conducted in the field.
- Provide semi-quantitative data. A score is assigned based on defined rules and scoring criteria.
- Be relatively low cost, quick and straightforward to perform by non-experts.

SOIL COMPACTION ASSESSMENTS

Penetration resistance

Penetration resistance is measured using penetrometers, which measure the force required to push a probe through the soil at a constant speed.

Penetration resistance is a good predictor of soil porosity and the ease with which roots can penetrate the soil.

Bulk density

Bulk density is the weight of soil in a given volume.

Can be used to measure soil compaction, water content, soil porosity and thermal conductivity.

SOIL WATER ASSESSMENTS

Infiltration rate

The infiltration rate refers to how quickly water passes through soil. This can be measured using an infiltrometer and calculated using an equation.

This can be time consuming because it requires multiple measurements to be accurate.

Modelling

Modelling can also be used to describe the hydraulic properties of soil based on easily measured data.

SOIL REMOTE SENSING

Remote sensors collect data about soil properties by detecting the energy that is reflected from Earth.

These sensors can be mounted on satellites, on aircraft or even on drones and measurements are taken in the field.

Remote sensors can be hampered by vegetation and cloud cover. On-the-ground data collection is still required to maintain the reference databases.

MODELLING

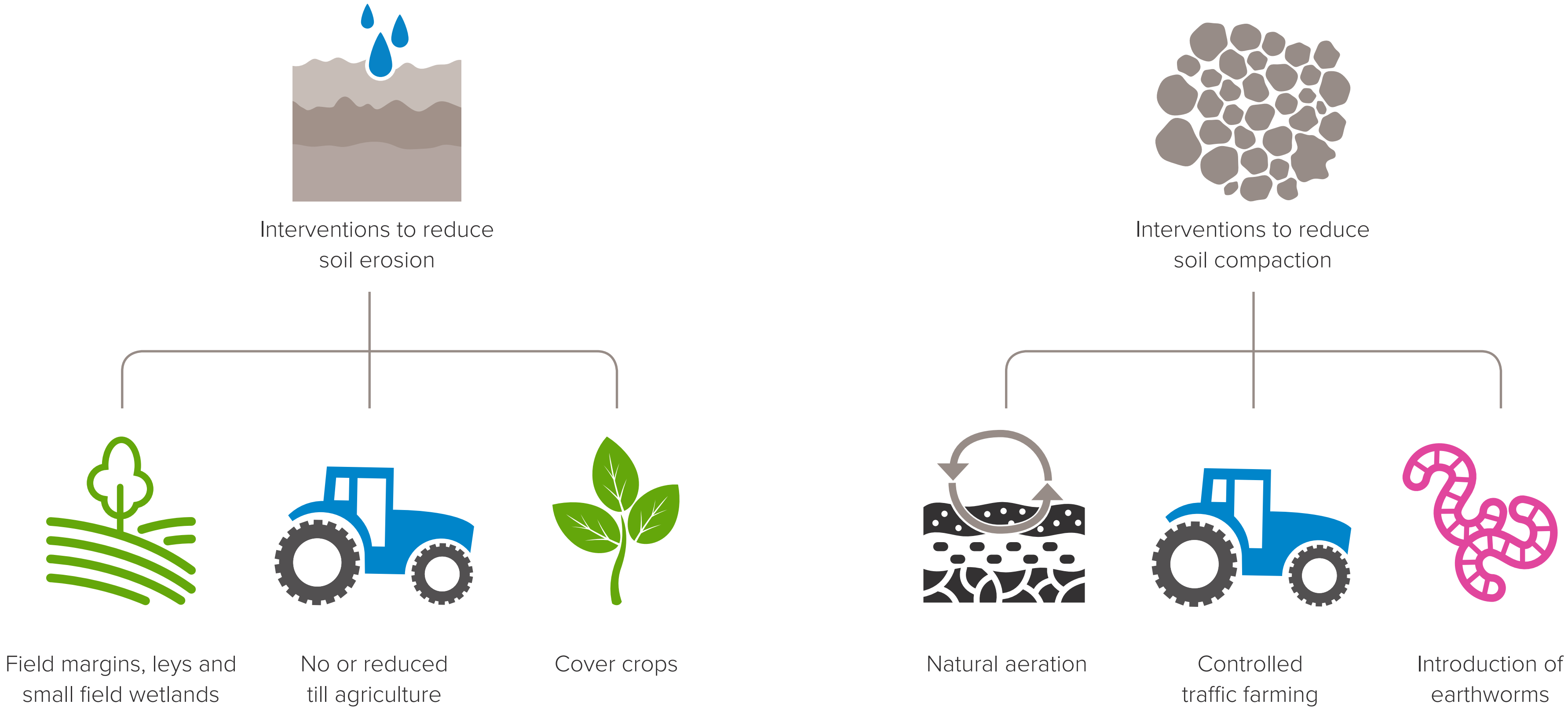
Models can be a powerful and low-cost method for describing natural systems, including soil.

Models can combine multiple pieces of information to generate an overall rating of soil quality.

However, the usefulness of a model depends on the completeness and relevance of the datasets used to build it, and land use data, soil data and digital elevation data can be spatially incomplete or out of date.

Interventions

Examples of possible interventions by land managers are summarised below. There is no ‘one-size-fits-all’ intervention, due to the variations in climate, soil and crop type across the UK.



Discussion

CONCLUSIONS

Many of the benefits from soil structure can be delivered in parallel.

Beneficial interventions and optimal land management are very context and site specific.

Soil management frameworks need to be flexible enough to allow farmers and land managers to optimise the range of benefits delivered and minimise trade-offs.

Measures of soil structure which lend themselves to a new incentives scheme are likely to be semi-quantitative approaches that farmers and land managers can use themselves, inexpensive and not time consuming.

Illustrative examples

Below are four examples that have been developed to illustrate some of the findings presented in this evidence synthesis and some of the options available to policymakers. Please note that these are purely hypothetical and do not represent Royal Society policy positions or recommendations.

ILLUSTRATIVE EXAMPLE 1

Incentives for a low-tech, voluntary, soil monitoring programme that relies on participation by farmers.

Cost

Small increase in government spending to receive and process scorecards. Medium increase in spending to fund training and advice schemes for farmers. Medium increase in government spending to fund incentives and auditing. Small increase in time required by land managers to complete the scorecard.

Benefits

Farmers can make informed decisions. Creation of a semi-quantitative database.

Disbenefits

There may be inconsistencies in how the data is collected. Voluntary scheme might not increase engagement and may only incentivise existing well performing farms.

ILLUSTRATIVE EXAMPLE 2

Incentives for a scientifically rigorous soil monitoring scheme at farm scale.

Cost

High cost to government for training, engagement, incentives. Minimal cost to land managers.

Benefits

This approach would allow quantitative data to be gathered on a subset of UK agricultural soil. This data could be of use to multiple different parties, including academic researchers, policy officials, environmentalists, water treatment companies, and land users.

Disbenefits

Lack of engagement from land managers could prevent systematic data collection so clear communication of the benefits to land managers is vital.

ILLUSTRATIVE EXAMPLE 3

New regulation, including incentives and penalties.

Cost

High cost to government.
Medium cost to land managers.

Benefits

All farms required to take part so not subject to sampling bias. Market forces could encourage land managers to take action.

Disbenefits

It may be highly unpopular with farmers if it is felt that the scoring by the regulators prioritises one land use, soil type or land management system over another.

ILLUSTRATIVE EXAMPLE 4

Maintain the status quo.

Cost

N/A

Benefits

Some farmers are already managing their soil to a high standard. Additional services from other parties can be helpful in providing training at no cost to the taxpayer.

Disbenefits

Without a national database, the current baseline for soil quality in the UK is unknown and opportunities to meet current or future government targets, legislation or even reduce government spending overall can be missed. Not addressing soil degradation could lead to yield losses and increased costs to farmers and wider society.

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