Soil structure and its benefits

An evidence synthesis

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Contents

Executive summary

Soil provides a wide range of benefits to human society, including agricultural productivity, clean water and flood prevention, and climate change mitigation. In addition, soil contains high levels of biodiversity and directly supports ecosystem services and other terrestrial biodiversity.

This report synthesises the evidence on the relationship between soil structure and benefits, focusing mainly on agricultural, mineral soil. Soil provides a wide range of benefits to human society, including agricultural productivity, clean water and flood prevention, and climate change mitigation. In addition, soil contains high levels of biodiversity and directly supports ecosystem services and other terrestrial biodiversity.

There is growing awareness of the importance of soil structure, particularly its porosity and permeability to water and gases, for the delivery of these benefits. Good soil management is therefore of paramount importance. Despite this, there is currently no single policy dedicated to maintaining high quality soil at the United Nations (UN), European Union (EU) or UK national level. The UK's departure from the EU presents an important opportunity to ensure that UK policies relating to soil health incentivise best practice in land management.

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. It summarises the measurements that can be used to monitor soil structure and the interventions that land managers can make to improve the structure of their soil. The report concludes with a series of illustrative examples to demonstrate the trade-offs and co-benefits that can arise from the different interventions to improve soil structure.

Summary of findings

Our findings specify the benefits that arise from maintaining a well-structured soil.

Biodiversity

Biodiversity and soil structure are closely linked; soil structure influences the nature and activity of soil organisms, while soil organisms affect the physical structure of the soil. Good soil structure benefits a number of species and habitats. In addition, soil biodiversity, and its associated influence on soil structure, contributes to a range of ecosystem functions such as decomposition of dead matter and nutrient cycling. Soil also contributes to ecosystem services such as support of above-ground biodiversity, control of plant, animal and human pests and diseases, and climate regulation.

Agricultural productivity

Soil is required for 95% of global food production[1]. There is a correlation between improvements in soil structure and increasing grain yield of cereals[2]. A well-structured soil can improve crop productivity through providing a habitat for earthworms and other soil organisms. Compacted soil is often associated with a decrease in yield through detrimental effects on the crop's root system. Improved soil structure can help to prevent soil erosion, where the upper layer of soil is displaced. Soil erosion significantly affects the productivity of soil, with Defra estimating that the total cost of erosion in England and Wales is in the region of £150 million a year[3].

Clean water and flood prevention

Soil can act as 'natural flood management infrastructure'[4] by increasing water infiltration into the ground and also by providing natural water storage, for example through uptake into root systems. However, both these benefits are negatively affected by compacted soil structure. Compaction of the pores within the soil reduces the ability of rainfall to infiltrate the soil[5] and acts as an obstacle to root penetration[6]. The degree to which soil can contribute to flood prevention is strongly reliant on it being well-structured. When water flows over the surface of the land it can also have negative impacts on water quality. For example, rather than steadily infiltrating the soil, surface runoff can increase the erosion of topsoil and wash chemicals out of the soil and into aquatic ecosystems, potentially leading to the pollution of waterways and eutrophication[7].

Climate change mitigation

Soil is the largest terrestrial store of organic carbon and its potential as a carbon sink means it could have an important role in climate change mitigation. There is growing interest in soil management practices that help increase levels of soil carbon stocks. Many interventions that improve soil carbon levels also improve soil structure and contribute to the maintenance of healthy soil. There is debate over the extent to which practices that increase soil organic carbon can play a role in climate change mitigation. The capacity for soil carbon sequestration depends on soil type and land use. For example, the soil of wetlands and peatlands accumulates carbon at faster rates, due to high soil moisture and decreased rates of microbial decomposition[8,9]. Changes in land use can have large impacts on soil carbon levels. Meta-analysis studies have shown that land use conversion from forest to agriculture results in loss of soil organic carbon[10,11]. In contrast, the restoration of former crop fields to grassland or forests can restore soil carbon[12].

Win-wins, trade-offs and caveats

All of the benefits described here can be delivered in parallel, with good soil structure leading to increased yields, enhanced biodiversity, improved carbon sequestration and improved water storage. However, there may be some trade-offs in terms of prioritising or enhancing one of these benefits above others. For example, interventions to reduce erosion and improve water quality may lead to short-term reductions in crop yield.

What is less clear from the published evidence is the relationship between an action to improve soil structure (for example adding more organic residues back to the soil) and the magnitude of change in the associated benefit (for example the increase in soil organic carbon). Furthermore, quantifying the scale of an intervention's benefits to farmers and land managers is difficult due to the variability in measures of soil structure. The UK has over 700 soil types, determined by variations in geology, climate, plant and animal ecology, and land use[13]. It can therefore be difficult to monitor when and why 'meaningful' changes to soil structure (for the better or for the worse) have occurred[14].

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Semi-quantitative approaches that farmers and land managers can use themselves, and that are also inexpensive and quick to apply, have the advantage that they can be used repeatedly over time, and by the main user of the land.

Soil structure is just one element of well-functioning soil. Thus, a measure of soil structure may be of little relevance if the soil of concern is providing a platform for human activities, or storing geological and archaeological heritage[15].

Trade-offs also exist for potential metrics of soil structure that could be used to incentivise good soil management within a future agricultural policy. Semi-quantitative approaches that farmers and land managers can use themselves, and that are also inexpensive and quick to apply, have the advantage that they can be used repeatedly over time, and by the main user of the land. They can provide an overall indicator of whether different visual aspects of the soil are 'good' or 'poor', which may be enough to inform land managers, farmers and government on whether the soil is generally improving or degrading over time. However, these approaches would be unsuitable for the development of a rigorous and reliable national soil monitoring programme, which would require measures to collect objective data that could be analysed statistically, and ideally could provide information on a regional or even global scale[16].

The appropriateness of semi-quantitative and fully-quantitative measurements depends on the desired outcome. If the aim is to improve soil quality through a participative, low cost, decentralised system that incentivises land managers to engage and self-evaluate the impacts of their land management techniques, then the semi-quantitative approach may be the most appropriate. Alternatively, a soil monitoring approach that uses the expertise of agricultural scientists, with techniques that are more expensive but more detailed and objective, may be more appropriate for mapping the current state of soil across the UK and demonstrating more detailed trends over time. Either of these approaches could feasibly be used as part of a new land management policy. The two approaches are not mutually exclusive, and it may be that both could be used in a tiered approach. Any future approach should be designed with industry support and participation from farmers, retailers, water treatment companies and other stakeholders. It will be important to ensure that land managers in the future have access to a practicable set of indicators to monitor and clear standards to meet.

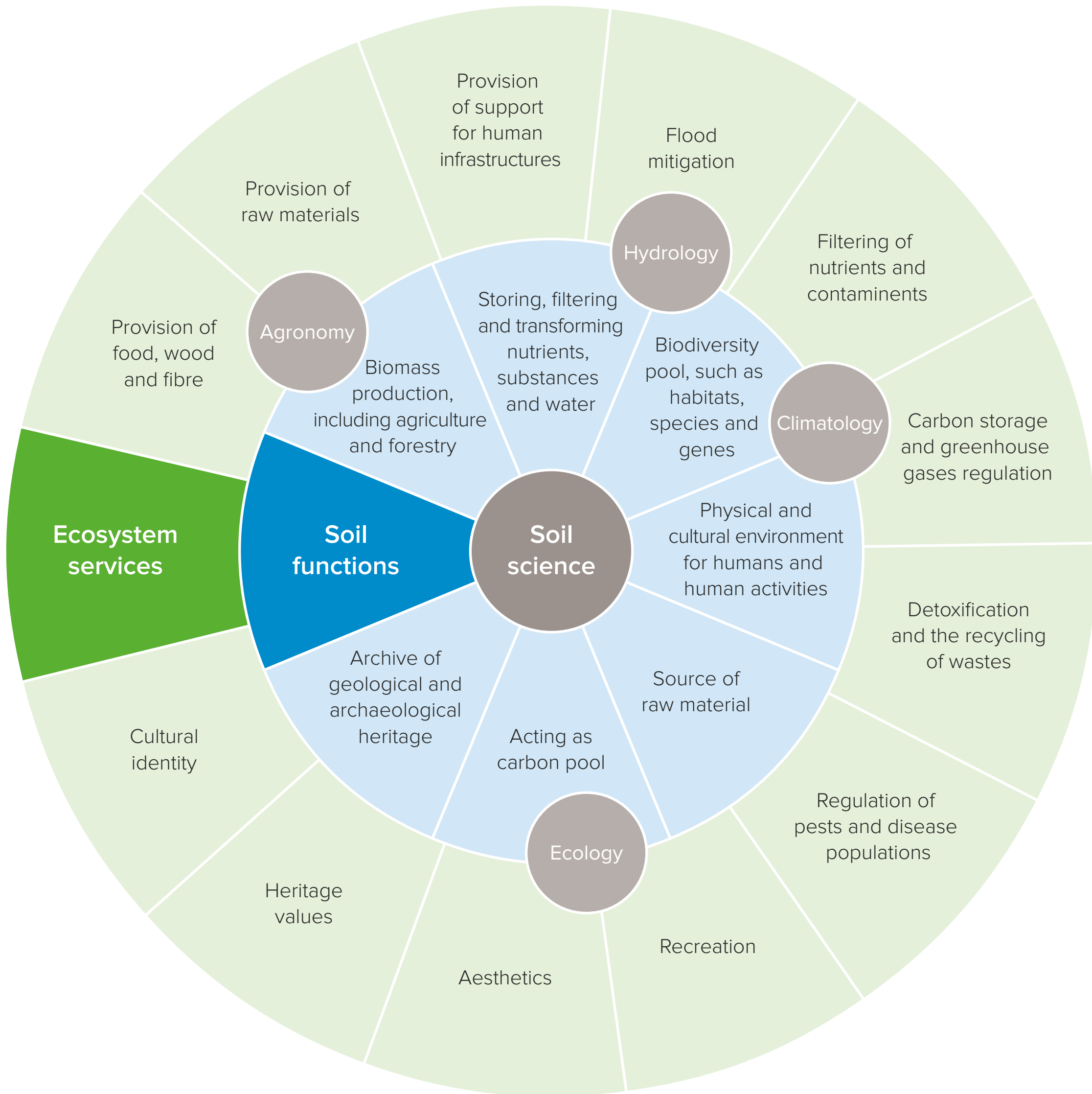
Introduction

Soil provides a wide range of benefits to human society (Figure 1), including producing food, providing clean water, reducing the risk of flooding and mitigating climate change through carbon sequestration.

Soil contains high levels of biodiversity – ten grams of soil may contain 10 billion bacterial cells, representing more than 1 million species[17] – and directly supports other terrestrial biodiversity.

FIGURE 1

The range of functions and services that soil provides[18].



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[19].

Soil is included across a wide range of different United Nations (UN) goals and agreements[20], European Union (EU) policies[21] and directives[22,23] and national policies and legislation[24,25,26] amongst others. However, while soil is currently subject to a variety of international and national targets, there is currently no single policy dedicated to soil at the UN, EU or UK level, unlike for example the EU Water Framework Directive for water. This issue was highlighted in the 2016 Parliamentary Inquiry into Soil Health by the Environmental Audit Committee[27]. Examples of UK policy in relation to soil include a pledge by the UK Government that all of England's soil will be managed sustainably by 2030[28]. More recently this has been reaffirmed in the Government's 25 Year Environment Plan which states that "by 2030 we want all of England's soil to be managed sustainably, and we will use natural capital thinking to develop appropriate soil metrics and management approaches"[29]. The Welsh Government includes the loss of soil carbon as one of the national indicators tracking progress towards achieving its seven well-being goals[30].

Alongside policy mechanisms, good soil management is promoted by incentives offered to farmers and land managers by supermarkets, food production companies and water treatment companies. Some examples of these are given in Box 1.

BOX 1

Examples of soil management incentives offered by industry

- Marks and Spencer have launched 'Plan A 2025', an eight-year transformation plan focussed on social and environmental issues, including soil health[31]
- Nestlé have partnered with First Milk to incentivise farmers to improve environmental sustainability (including soil). The scheme sees farmers being paid directly through their contracts for delivering quality agri-environment work through a points-based system[32]
- ASDA have collaborated with LEAF (Linking Environment And Farming), to produce 'six simple steps' for farmers to improve the performance, health and long-term sustainability of their soil[33]
- Wessex Water Ltd, a water and sewerage business serving the south west of England has also used various means – including advice, negotiation and financial contributions – to change the practices of farmers and landowners to reduce soil erosion and runoff to improve water quality[34]
- Tried & Tested is a voluntary initiative delivered by a series of industry partners and aims to help farmers to improve nutrient management planning through practical nutrient, manure and feed planning guidance[35]
- CFE is a partnership initiative which promotes good environmental management through productive farming practices[36]

As the UK leaves the EU, a new agricultural policy will replace the current Common Agricultural Policy (CAP). It is important to ensure that UK and devolved administration policies and incentives relating to soil promote best practice in land management to deliver multiple beneficial outcomes. For England, the new Agriculture Bill will include a payment scheme based on 'public money for public goods' and this explicitly mentions rewarding good soil management[37]. In Wales a new Sustainable Farm Scheme is under development around the principle of sustainability[38] while in Scotland many current CAP schemes will continue as under the EU, at least in the short term[39]. In Northern Ireland, a move away from area-based payments is under consideration. In all instances, evidence connecting the action or intervention taken by the farmer or land manager to a feature (such as soil structure) and a beneficial outcome will be vital.

Focus of this synthesis

This evidence synthesis summarises the published evidence about 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 selected as the topic of focus following two stakeholder workshops in March and July 2019. Soil structure was chosen due to its relationship with water and gas permeability and the beneficial outcomes that this permeability supports – such as those described in Chapter one. 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.

There are a range of different soil types and therefore the management and range of benefits provided are likely to be very context specific. The majority of the scientific literature focuses on the structure of mineral soil (where the parent material is rock), which makes up the majority of UK agricultural soil. It is for this reason that the evidence synthesis will focus primarily on the soil structure and benefits of mineral soil of managed grassland or arable land. For inclusion criteria please see Annex 2: Methodology.

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.

Soil structure

A description of soil and its structure is provided in Box 2. 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[40]. These features enable functions, such as nutrient cycling and water and oxygen transport, which promotes ecosystem services such as increasing soil fertility and water purification. In this synthesis, we will refer to soil with these features, as 'well-structured'. In addition to supporting food production, many of these soil structural features also provide a range of other benefits. These are explored in detail in Chapter one. For other soil types, outside the scope of this synthesis, we note that the qualities of a 'well-structured' soil will be different.

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BOX 2

Mineral soil and its structure

What is soil?

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

Soil develops gradually over time, as weathering of the bedrock on the Earth's surface combines with decaying organic matter. Soil typically develops in layers (also known as horizons) which are distinct from one another in colour and texture (Figure 2). The bottom layer, the bedrock, is a solid mass of rock and provides the 'parent' material for the soil and influences its type. For example, clay particles are derived from fine-grained rocks such as shale while sandy particles tend to come from the weathering of sandstone. Soils formed over chalk and limestone are naturally thin because these rocks do not give rise to clay or sand particles. Partially weathered rocks form the basis of the parent rock layer.

Unless regularly ploughed, the topmost layer is made up of organic matter, including leaf litter, at various stages of decomposition. Below is the surface soil (often referred to as 'topsoil') which is typically 10 – 25 cm deep. Topsoil is a combination of organic and mineral components; it usually has the highest biodiversity and the most nutrients. The layer below, the subsoil, has a similar composition although contains more minerals which have been leached (moved down) by rainwater.

The three main types of soil particle are clay, sand and silt. Note that silt in this instance refers to soil which originates from the erosion of rock and is not associated with river deposits. These three types vary in the size of their constituent particles, which leads to different properties (Table 1). The combination of these three particles determines the soil type (Figure 3). Soil type and structure have important ramifications for how soil behaves under different weather conditions and land management regimes. It is important to consider the type of soil present in fields for a number of reasons: to assess the risk of drought or flooding; to determine the vulnerability of the soil to compaction; and when considering the measurement of the characteristics of soil degradation, as all of these differ between the different soil types.

What do we mean by soil structure?

We refer to soil structure as the arrangement of solids and pore spaces within soil. Soil solids are soil minerals and organic particles that (with metal ions, organic matter, root hairs, bacterial secretions and fungi) 'clump' together to form aggregates. Aggregates (also known as peds) vary in composition, shape and size, and in their stability towards the erosive forces of water. The size and continuity of soil pores surrounding the aggregates is important for air, water and nutrient transport.

Soil structure influences water retention and movement, root penetration, carbon storage, susceptibility to erosion, and fertility – meaning it underpins many benefits.

TABLE 1

Properties of soil particle types[42].

Soil particle type	Particle size (mm)	Water retention	Characteristics
Clay	< 0.002	Drains slowly, high water retention	Heavy, slow to warm up, prone to compaction and drying out in summer
Silt	0.002 – 0.05	Retains a moderate amount of water	Easily compacted and prone to erosion
Sand	0.05 – 2.00	Fast draining, therefore often dry	Warms up quickly, often acidic

FIGURE 2

A mineral soil profile.

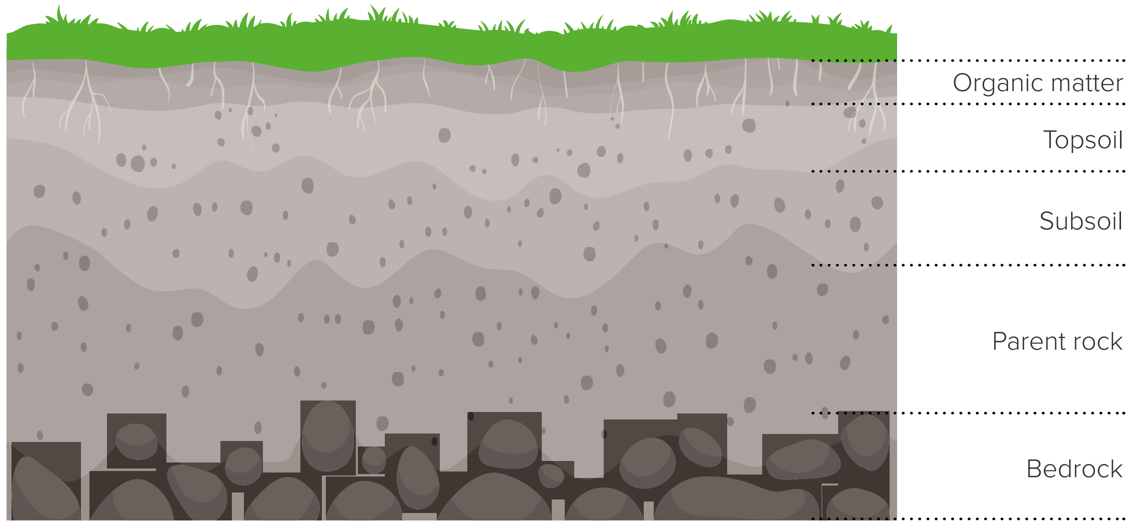
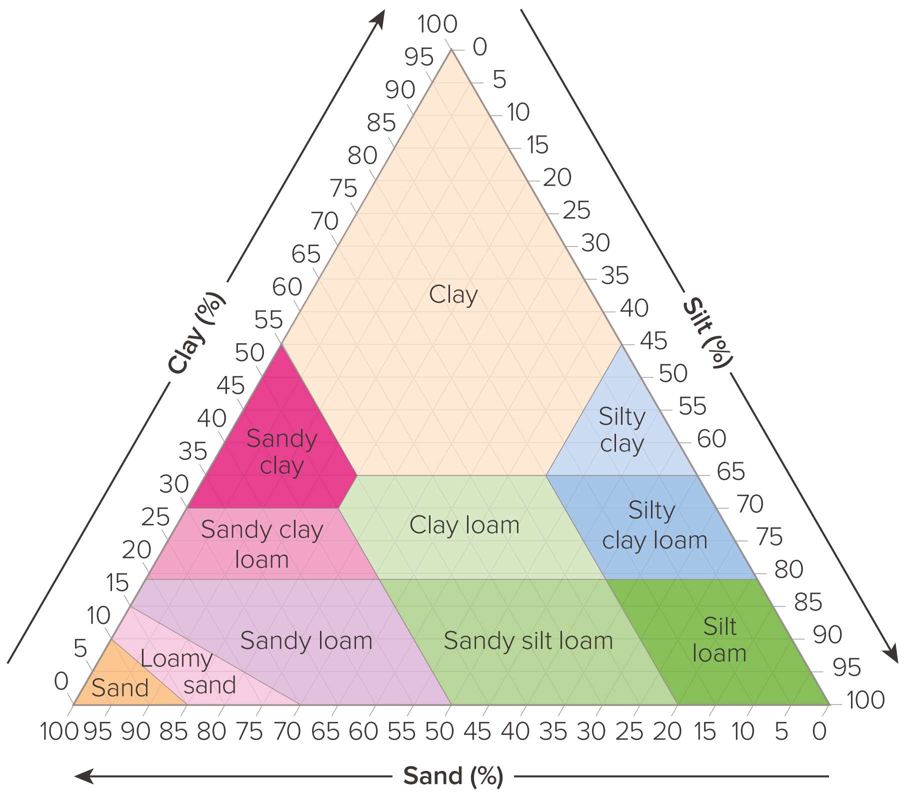


FIGURE 3

Soil texture triangle, showing the different soil types and combinations of clay, sand and silt particles[41].



Soil structure and associated benefits

The previous chapter described the characteristics associated with well-structured soil. 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. See Box 3 for more detail on the distinction between natural capital assets, ecosystem services and ecosystem benefits. This chapter examines the role of soil structure in delivering some of these benefits.

BOX 3

Natural capital assets, ecosystem services and ecosystem benefits[43]

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). See Figure 4 for further examples.

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.

FIGURE 4

Flow of natural capital assets, ecosystem services and the benefits that can be obtained[44].

Natural capital assets, for example:	Ecosystem services provided by these assets, for example:	Benefits obtained, for example:
Species	Pollination	Food
Communities	Biomass	Energy
Landscapes	Carbon sequestration	Clean water
Ecosystems	Erosion protection	Clean air
Soil	Water purification	Recreation
Water		Hazard protection
Air		Wildlife conservation
		Equitable climates

The remainder of this chapter presents the evidence linking soil structure in agricultural soil with the four following benefits:

- Biodiversity
- Agricultural productivity
- Clean water and flood prevention
- Climate change mitigation

Biodiversity

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 organisms and soil structure are closely linked and have a reciprocal relationship: soil structure influences the nature and activity of soil organisms and other terrestrial organisms, while soil organisms affect the physical structure of the soil and support well-functioning soil and wider ecosystems.

This section identifies where good soil structure is linked to biodiversity and also how soil organisms can improve soil structure and functioning. We define biodiversity as "the variability among living organisms from all sources including, [among other things] terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems"[45]. It is important to note that an increase in biodiversity does not necessarily correlate to 'useful' biodiversity; an increase in biodiversity could mean an increase in pathogens or pest populations. The chapter will identify the types of organisms that are beneficial to soil structure and functioning.

How soil structure supports biodiversity

Soil structure supports biodiversity by providing a habitat for the many organisms that live within it. 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 (Figure 5). It is estimated that soil and leaf litter is home to about one quarter of vertebrate and invertebrate species on the planet[46]. This level of biodiversity is supported by the diverse microhabitats that well-structured soil provides and that are created through variations in soil structural features such as soil texture (the relative content of soil particles of different sizes eg clays, silts and sands), water availability and nutrient availability.

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[47]. The ability of soil structure to hold moisture is linked to a high microbial diversity and more robust populations of soil mesofauna (animals between 0.1 – 2 mm in size, such as tardigrades, Figure 5e) and macrofauna (animals more than 2 mm in size, such as earthworms, Figure 5k) compared to dry soil[48]. Likewise, in one study the diversity

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and composition of fungal communities was strongly influenced by soil type and land use intensity[49]. Critically, soil biodiversity should not be treated as a single entity but as a complex array of communities, which are differently affected by various factors. This was demonstrated in a UK-wide study where animal richness was predominantly determined by land use intensity and unaffected by soil properties, whereas microbial richness was driven by broader environmental properties, including soil[50].

FIGURE 5

A selection of organisms in soil communities[51].

(a) root fungi	(b) decomposer fungi	(c) bacteria	(d) nematode	(e) tardigrade
(f) collembolan	(g) mite	(h) worm	(i) millipede	(j) centipede
(k) earthworm	(l) ants	(m) woodlice	(n) flatworm	(o) mole

How soil biology supports soil structure

Soil organisms contribute to a range of ecosystem functions (see Figure 1 and Figure 4) such as nutrient cycling and soil formation, and ecosystem services, such as the control of pests and diseases, as well as supporting above ground biodiversity[52]. However, the relationships between species diversity and ecosystem functions and services are complex; the direction and strength of the effect of species diversity varies highly and other factors may also play a role in driving ecosystem functioning[53].

Certain organisms, such as plants and their associated root systems or animals such as earthworms, act as 'soil engineers' and can modify soil structure, pore size, porosity, bulk density, organic matter and water content[54].

Plants and their root systems influence the physical and biological properties of the soil[55]. Denser, finer root systems bind soil more effectively than thicker, sparser root systems, and thereby increase soil stability[56]. The growth of roots physically displaces soil particles; hence, larger roots increase soil density adjacent to the root, whereas finer roots can decrease density by increasing soil porosity[57].

The release of organic compounds by root systems, known as root exudates, into the surrounding soil systems has been shown to act like a glue and bind soil particles together. Root exudates increase soil stability and in the longer term have been shown to reduce the ability of water to flow through the soil[58,59]. Additionally, root exudates strongly influence the composition of soil microorganisms[60]. Mycorrhizal fungi, beneficial fungi that form a symbiosis (close interaction) with plant roots, can also change the soil structure by physically enmeshing soil aggregates in their hyphae (the branching structures of fungi). Recent evidence suggests that a particular glycoprotein released by certain mycorrhizal fungi is involved in the aggregation of soil particles[61].

Soil microbial communities can directly affect soil structure and functionality through their roles in cycling soil nutrients and storing carbon[62]. Microbes known as cyanobacteria produce extracellular substances that alter the soil pore structure and form biological soil crusts. These soil crusts help to stabilise the soil. Once the cyanobacteria have colonised and created a soil crust, other organisms such as fungi, lichens, bryophytes, and algae also colonise the crust[63]. This helps to prevent soil erosion in arid or wet regions and aerates the soil. This aeration by microbes also helps to cycle nutrients by decomposing organic matter, making vital nutrients such as phosphorus, potassium and nitrogen available to be taken up by plants[64].

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Earthworms have an important role in maintaining and enhancing soil structure. They act as 'ecosystem engineers' by physically burrowing in, and aerating, the soil and strongly influence the physical and chemical characteristics of soil layers[65]. They play a vital role in mixing organic matter in the soil[66], cycling nutrients[67] and creating new microhabitats for soil organisms[68]. Earthworm burrows also increase water filtration and reduce runoff on the soil surface, thus reducing soil erosion.

Human agricultural activity can have a strong impact on soil biological activity and diversity[69]. Tillage, which involves digging, stirring and turning over soil, strongly reduces the numbers of most organisms within the soil[70,71]. Soil compaction by agricultural machinery has been shown to reduce soil microbial biomass[72], and reduces soil pore size which affects the movements of worms and larger soil animals[73]. Earthworm populations have been reported to decrease in response to soil compaction[74].

Certain managed farm systems can change the nature and complexity of the communities found in soil[75]. A meta-analysis revealed that more intensively managed soil is associated with higher levels of microbial richness (number of species), but leads to declines in the number of larger soil animals such as earthworms[76]. It is important to consider 'functional biodiversity' in these cases; there may be instances where the overall number of species may be higher in one system, for instance due to a higher number of microbes, but it may not have the same beneficial effects as a soil ecosystem that contains organisms of a range of sizes that carry out a range of functions.

Changes to the balance of communities of soil organisms has implications for the resilience of food production in the face of extreme events. Bacterial dominated communities are slower to recover from drought events[77]. As more extreme weather events occur in the future, resilient food production is likely to become increasingly important; functional soil biodiversity may have a role in supporting this[78].

The role of soil structure in promoting agricultural productivity is explored in the next section.

Agricultural productivity

Soil is required for 95% of global food production[79]. Over the next 30 years, our food system will experience an unprecedented demand as global population increases to 9.7 billion people by 2050[80]. Meeting the nutritional demands of 2 billion more people may require either radical societal adaptation (eg replacing most meat and dairy with plant-based alternatives[81]), or a considerable increase in the efficiency of global agricultural production, distribution and waste management[82], and most likely a combination of all of these measures. Here we describe the ways in which soil structure can enhance agricultural yields.

It is well known that soil structure can affect crop yield[83]. One study in which soil structure was visually scored (with a high score (9 – 10) indicating a good soil structure and a low score (1 – 2) indicating a poor soil structure that 'consists entirely of big clods, smooth dense crack faces, roots only in cracks'[84]), found there was a correlation between good soil structure and higher grain yield of cereals. It found yield increases of 300 – 350 kg ha^{-1} for each unit increase in the soil structure score[85].

A high density of earthworms is linked to improved agricultural productivity. 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[86]. A 2014 study found that on average earthworm presence in agricultural soil leads to a 25% increase in crop yield and a 23% increase in aboveground biodiversity[87]. Well-structured soil can affect crop productivity by providing a habitat for earthworms. Earthworms can be negatively impacted by certain farm management systems. A global meta-analysis revealed that conventional till regimes decrease the abundance of earthworms[88]. One study indicated significantly reduced earthworm numbers with increased fertiliser and pesticide inputs[89].

Compacted soil occurs under the wheels of tractors and heavy machinery, and this is associated with decreases in crop yield due to detrimental effects on the crop's root system. Compaction also reduces water infiltration and water uptake[90]. Compaction from machinery can be reduced through the use of fixed tracks for wheels (to achieve non-trafficked crop growing zones). For example, implementing non-trafficked zones (as measured by soil porosity) significantly improved the structure of topsoil when compared with conventional random traffic farming – this correlated with an average yield increase of 6 – 10% in green peas, spinach and planted onions[91].

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The most recent estimate of the impact of erosion on productivity losses was around £40 million a year in England and Wales, as a result of reduced yield and increased costs, with the total cost of erosion in England and Wales in the region of £150 million a year.

The physical structure of the soil also determines the likelihood of soil erosion, which can negatively affect agricultural productivity. 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[92]. Erosion is estimated to move around 2.2 million tonnes of topsoil per year in the UK alone, with the soil often ending up in watercourses[93]. The topsoil layer contains the highest concentration of organic matter and microorganisms and thus its loss significantly affects the productivity, structure and functionality of the soil. The most recent estimate of the impact of erosion on productivity losses was around £40 million a year in England and Wales, as a result of reduced yield and increased costs, with the total cost of erosion in England and Wales in the region of £150 million a year[94]. A review of 24 studies in the UK found that yields decreased on average by 4% per 10 cm depth of soil loss through erosion[95].

Agriculture relies on well-structured soil for its ability to store and provide water to plants. The role of good soil structure in providing clean water and flood prevention is explored in the next section.

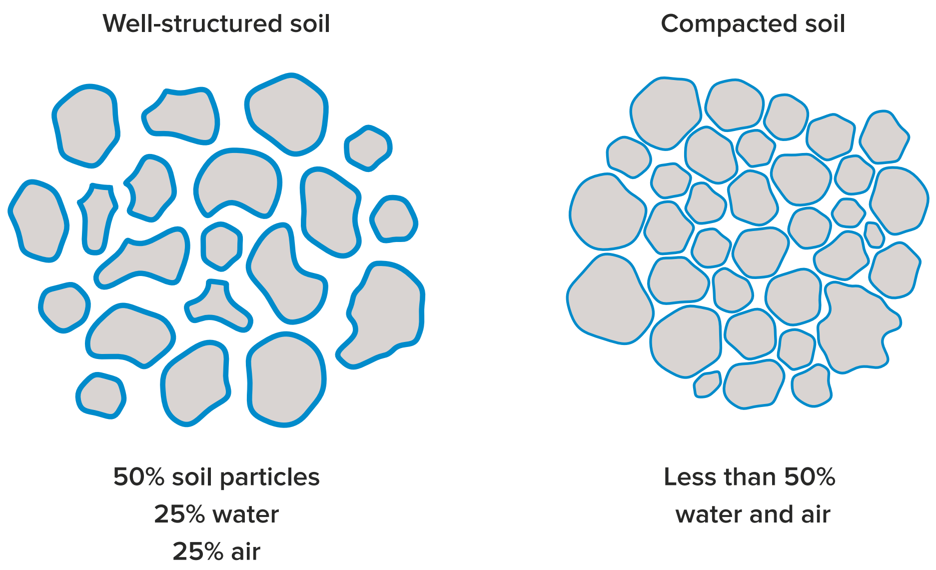
Clean water and flood prevention

Well-structured soil filters water between the atmosphere, groundwater, lakes and rivers, improving water quality and availability. Soil water represents only 0.05% of global freshwater and 0.001% of global water[96], yet is crucial for supporting all terrestrial life.

Soil is made up of solid particles, air pockets (or pores) and water (Figure 6). The effectiveness of soil water storage depends on the soil texture and on the pore space between soil particles, which is determined by factors such as soil organic matter[97]. The pore size distribution affects aeration, water holding capacity, and drainage capacity of soil[98]. When soil structure is degraded due to compaction, the pores are pressed together, reducing the space where air and water are normally stored (Figure 6). This significantly reduces the ability of water to vertically infiltrate the soil and thus increases surface runoff and the risk of flooding[99]. It also limits the pathways available for crop roots, affecting agricultural yields[100], and leads to greater soil erosion and the pollution of waterways[101].

FIGURE 6

Soil compaction reduces the available space for soil, air and water, limiting pathways for root growth[102].



Flooding and surface runoff

Soil can act as 'natural flood management infrastructure'[103] 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. Well-structured soil structure reduces surface runoff.

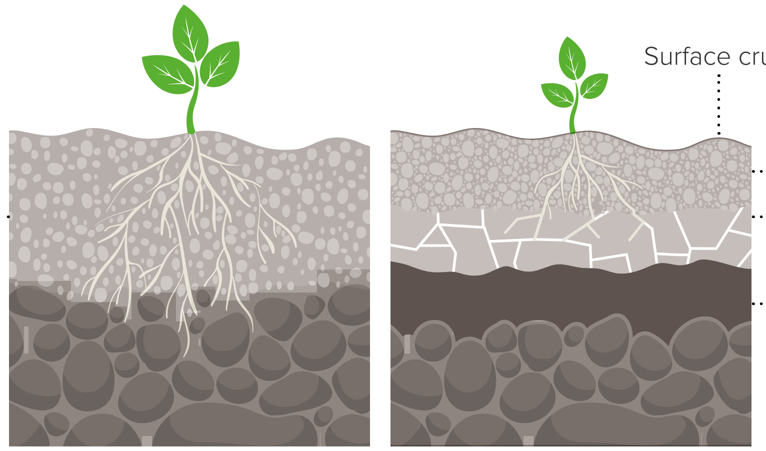
The amount of water retained in soil (available water capacity) is positively related to levels of soil organic matter. Soil organic matter enhances soil water retention because of its hydrophilic (water-attracting) nature and ability to increase soil aggregate formation and stability, thereby enhancing porosity and infiltration[104].

Compaction damage changes the soil pore structure and reduces the ability of soil to absorb heavy rainfall, leading to the rapid flow of water into lakes and rivers[105]. Subsoil compaction can lead to the formation of a plough pan (Figure 7), a layer in the subsurface of the soil that has a high density and a lower porosity than the soil directly above or below it. This is the result of pressure applied by machinery during tillage. With tillage, the formation of a plough pan in the subsoil changes the direction of water flow through the soil by impeding vertical infiltration and enhancing the horizontal flow[106]. This results in two major issues depending on the time of year: 1) it can increase the risk of flooding in winter and 2) reduce the soil's capacity to deal with heat shocks in summer[107,108].

Well-structured soil filters water between the atmosphere, groundwater, lakes and rivers, improving water quality and availability.

FIGURE 7

Plants growing in (a) well-structured soil and (b) compacted soil[109].



Livestock grazing can also cause soil compaction. Root systems are affected by both topsoil and subsoil compaction, with compacted soil acting as an obstacle to root penetration (Figure 7)[110]. In one study, soil permeability on a highly grazed pasture was increased and rainwater runoff was reduced by reducing the number of livestock and planting trees[111]. In another study, water was found to infiltrate into forest hillslope soil, but run off the surface of sloped, compacted grassland soil. This was due to the larger root water uptake by trees, and lower soil moisture in the forest soil compared to the compacted grassland soil[112]. Thus, there is a need to appropriately value and preserve the 'green storage' of water by trees[113,114].

Soil compaction reduces the depth of crop rooting and the supply of water to root systems, reducing crop growth. This increases the likelihood of surface runoff and soil erosion. The water carries with it fine sediment, organic material, crop nutrients, pesticides and microbes[115]. It also results in an increased need for fertiliser input as chemicals are washed away rather than retained in the soil[116]. These chemicals can become contaminants in aquatic ecosystems and a threat to human health[117].

Soil moisture also has an important role in the regulation of another benefit derived from well-structured soil, the mitigation of climate change, as discussed in the next section.

Climate change mitigation

Soil structure and carbon sequestration

Soil is the largest terrestrial store of organic carbon, and contains twice as much carbon as the atmosphere[118]. Soil management and the resultant soil structure can affect the carbon content of soil[119]. 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)[120]. Even small changes in the soil carbon pool have the potential to significantly influence the concentration of carbon dioxide in the atmosphere. There is increasing interest in enhancing the carbon content of soil as a means of reducing the amount of carbon dioxide in the atmosphere. The Royal Society's report on greenhouse gas removal recommended that if the UK were to achieve its target to be net zero by 2050, a key action would be to 'ramp-up' soil carbon sequestration across large UK land-areas through changes in agricultural practices (see Box 4)[121] . There are a number of co-benefits of improving soil carbon sequestration (including improved soil structure) which makes such strategies to increase soil carbon 'win-win' or 'no-regrets' strategies[122].

Soil is the largest terrestrial store of organic carbon, and contains twice as much carbon as the atmosphere.

Carbon forms a significant part of the total soil organic matter, which consists of plant residues, living microbes, fresh and partially decomposed detritus (dead organic matter) and humus (stable organic layer). Soil organic carbon levels are therefore directly related to levels of soil organic matter and result from the interaction of several processes. Carbon enters long-term storage in soil as organic carbon from plant material and is incorporated into the soil through decomposition.

Input of carbon from the atmosphere to soil is indirect, enabled by plant photosynthesis, which converts atmospheric carbon dioxide into simple sugars. These sugars are incorporated into organic matter for plant growth or used as a source of energy. Decomposition of plants transfers the organic carbon captured from the air, into the soil. The constant flux of carbon in the environment is known as the carbon cycle, and is depicted in Figure 8.

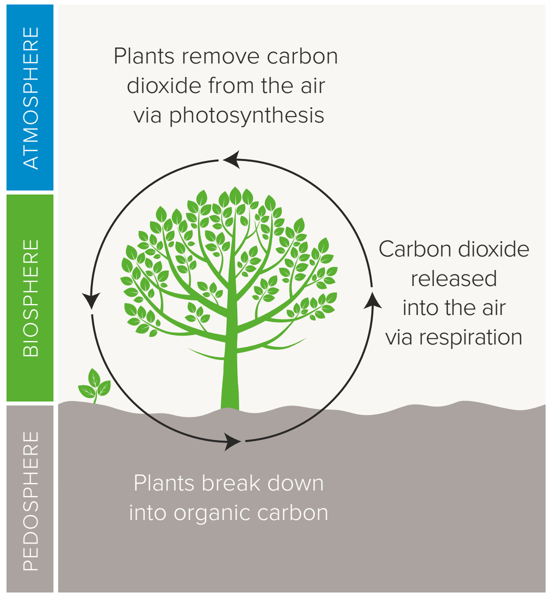
BOX 4

Agricultural interventions that enhance soil structure and may increase soil carbon storage

- Reducing tillage intensity and frequency
- Crop rotations – including use of grass and livestock
- Switching to perennial crops instead of annual crops
- Using cover crops and eliminating fallow periods (Figure 11)
- Applying of manure and sludge, and other waste materials
- Adjusting irrigation methods
- Changing grazing regimes
- Implementing conservation buffer strips
- Agroforestry

FIGURE 8

The carbon cycle.



Changes in land use can have large impacts on the capacity for soil carbon sequestration. Meta-analyses have concluded that conversion from forest to arable cropping systems reduces soil organic carbon[123,124]. Since 1750, between 40 and 90 billion metric tonnes of carbon has been lost from soil globally, through cultivation and disturbance[125 – 127]. However, carbon sequestration due to the restoration of former cropland to grassland or forests can reduce, or in rare cases even exceed, carbon deficits resulting from previous land use[128]. Therefore, croplands have high potential for future carbon sequestration and, with appropriate land management, can play an important role in climate change mitigation. This increase in soil organic carbon would also improve soil structure and the range of other soil functions and benefits which are associated with this.

Land management practices also affect soil structure and carbon sequestration (Box 4). Practices such as reduced till[129] and growth of soil cover crops have been shown to increase levels of soil organic carbon[130], though the extent to which this has a large role in climate change mitigation is debated[131,132]. Many of these interventions which improve levels of soil organic carbon also improve soil structure and contribute to other soil functions. In particular, the addition of organic matter to soil increases nutrients (reducing the need for synthetic fertiliser), increases water retention and reduces soil erosion. Measures to protect soil structure from compaction and degradation, such as optimisation of grazing intensity, also enhance organic matter content and hence carbon sequestration[133].

The use of perennial vegetation (crops which do not need to be replanted after each harvest) rather than annual crops also increases soil carbon. For example, perennial grassland has been found to have higher soil carbon throughout the soil profile, particularly as root and microbial biomass, than annual wheat agriculture[134]. The use of permanent vegetation in agricultural land, for instance with agroforestry (the intentional combination of perennial shrubs and trees with annual crops such as cereals) and conservation buffer strips (strips of land with permanent vegetation), can aid carbon sequestration, in addition to providing other benefits, such as improving soil quality and structure, reducing erosion and supporting wildlife. The associated improvement in soil structure will contribute to the increased regulation of water flows and other soil functions[135,136]. Interventions to stabilise carbon within the soil or even increase how much carbon can be sequestered are being investigated to help achieve net-zero emission targets and mitigate climate change[137,138].

When considering land management interventions to improve soil structure and carbon sequestration, for example through promoting an increase in soil organic matter, there are potential effects on other greenhouse gas emissions.

Soil organic carbon can be released back into the atmosphere as carbon dioxide via respiration of plants, soil animals and microbes, including decomposers. Carbon in the form of methane can also be released into the atmosphere from soil organisms when decomposition takes place in the absence of oxygen (eg under waterlogged conditions). Methane is produced in anoxic (low-oxygen) environments, including submerged soil, by microorganisms (methanogenic bacteria) that excrete it as a by-product[139]. Methane is a more potent greenhouse gas than carbon dioxide, with 34 times the global warming potential over 100 years[140]. However, increasing soil organic matter for carbon sequestration is expected to have only a negligible impact on soil methane emissions[141].

> Many interventions which increase levels of soil organic carbon, also improve soil structure and contribute to other soil functions. In particular, the addition of organic matter to soil increases nutrients and water retention, which reduces soil erosion.

The impacts of these climatic changes on soil structure include greater erosion and loss of soil organic matter.

Nitrous oxide is also a potent greenhouse gas and can be emitted from agricultural soil particularly where nitrogen fertiliser is used. Increasing soil organic matter or carbon sequestration would also increase organic nitrogen levels in the soil which could increase nitrous oxide emissions, though the likely effect is hard to quantify[142]. Emission rates of nitrous oxide are increased in wet and compacted soil[143,144]. The release of nitrous oxide from manure applications may offset any increase in soil organic carbon as a carbon sink[145].

The effect of climate change on soil structure

Soil structure and the ecosystems it supports are intimately linked to the climate. The production of carbon dioxide in soil comes almost entirely from root respiration and microbial decomposition of organic matter. Carbon cycle processes are temperature-dependent[146]. Moreover, environmental conditions beyond temperature contribute to changes in decomposition rate and carbon sequestration[147]. For example, dry or waterlogged (lacking oxygen) soil has decreased decomposition rates, sometimes leading to accumulation of soil organic carbon in areas such as peatland bogs. Furthermore, high levels of precipitation on fast-draining soil can lead to loss of carbon from soil through washing away dissolved organic carbon and soil erosion.

Climate change in the UK is expected to result in hotter, drier summers and warmer, wetter winters, and additionally an increased occurrence of extreme weather events such as drought, storms and floods[148]. The impacts of these climatic changes on soil structure include greater erosion and loss of soil organic matter[149]. Furthermore, wetter winters and therefore wetter soil, increases the risk of soil compaction from grazing livestock and livestock may have to be housed indoors for longer. Likewise, for arable farming, there will be a longer wait until the soil dries out in the spring and potential challenges with harvesting in the autumn, limiting the time available for soil management and tillage[150].

In addition to the effects on soil structure, climate change may also alter rates of soil carbon sequestration. Increased atmospheric carbon may increase plant growth and therefore increase carbon dioxide capture from the air into the soil through photosynthesis. However, due to erosion, loss of organic matter and changes to the frequency and intensity of droughts and flood events[151], climate change could also lead to a loss of carbon to the atmosphere. As a result, predicting the composite effects of climate change on soil is highly challenging[152,153]. A recent meta-analysis predicted that a business-as-usual climate warming scenario (ie a global average soil surface temperature increase of 2°C over the next 35 years) would drive the loss of between 5 – 115 billion metric tonnes of carbon from the soil by 2050[154]. It should be noted that the sites with the greatest losses were predicted to be wet, organic carbon-rich sites common in upland areas of the UK.

There are also indirect effects of climate change on soil structure and the role of soil in the carbon cycle, including changes in soil biodiversity and soil composition[155]. The effects of these changes on the decomposer community requires further research due to the complex interactions of temperature and moisture compounded by regional variations and differing soil types[156].

The next chapter of this evidence synthesis looks in more detail at some of the measurements used by land managers and scientists to assess soil structure and the benefits it can provide.

Measurements

This chapter summarises the currently available methods for measuring soil structure. There is substantial evidence that land management practices affect soil structure and therefore impact the benefits that soil can offer[157 – 159]. Part of the commitment in the 25 Year Environment Plan to manage England's soil sustainably by 2030, involves developing "appropriate soil metrics and management approaches"[160]. Detecting any deterioration in soil structure early is also important due to the long timescales (up to 190 years[161]) required for severely deteriorated soil to fully recover[162].

There is a vast array of methods to measure soil structure[163] with advantages and disadvantages to each. Measurements for soil structure suitable for use in the UK were recently reviewed[164]. The types of measurements differ by who conducts the measurement (typically either a land manager, academic scientist or soil consultant); where the measurement is performed (at the site itself or samples analysed in a laboratory); accuracy (for example whether they are based on discrete samples from a field or whether the entire field is measured); scale (from field to whole catchment); and finally, cost. The main groups of measurements that are performed on soil to measure its structure are summarised below.

Visual field assessments and scorecards

Visual assessments of soil conducted in the field offer the potential to gather semi-quantitative information for use in monitoring soil condition and avoid possible errors caused by transporting samples to a laboratory. Some assessments have been deliberately designed to be readily understood and easy to teach to non-soil scientists (for an example, see Table 2)[165].

A variety of visual soil description assessments exist including the SOILpak score[166] and Le profil cultural[167] and variations of one of the most well-known methods, designed by Peerlkamp[168].

Visual assessments differ in several important ways including the depth of the soil under consideration, how the soil is handled prior to assessment, and the emphasis placed on particular features of soil structure[169]. Most methods attempt to minimise subjective errors with clearly defined rules and scoring criteria[170]. They are relatively low cost and straightforward to perform, with experts suggesting that assessment of a soil sample by this method would typically take less than an hour when performed by an experienced user[171].

CHAPTER TWO

TABLE 2

Example of a visual soil assessment method where the soil is scored based on its visible structure and distinguishing features[172].

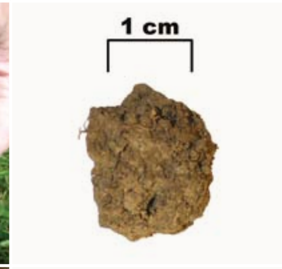
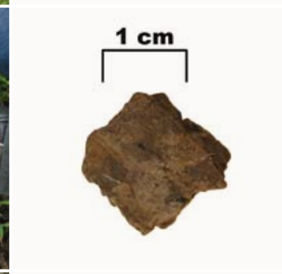
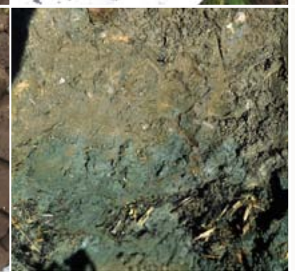
Structure quality	Ease of break up (moist soil)	Size and appearance of aggregates	Visible porosity	Roots	Appearance after break-up: various soil	Appearance after break-up: same soils different tillage	Distinguishing feature	Appearance and description of natural or reduced fragment of ~ 1.5cm diameter
Sq1 Friable (tends to fall off the spade)	Aggregates readily crumble with fingers	Mostly <6mm after crumbling	Highly porous	Roots throughout the soil				
Sq2 Intact (retained as a block on the spade)	Aggregates easy to break with one hand	A mixture of porous, rounded aggregates from 2 – 70mm. No clods present	Most aggregates are porous	Roots throughout the soil				
Sq3 Firm	Most aggregates break with one hand	A mixture of porous aggregates from 2mm – 10cm; less than 30% are <1cm. Some angular, non-porous aggregates (clods) may be present	Macropores and cracks present. Some porosity within aggregates shown as pores or roots	Most roots are around aggregates				
Sq4 Compact	Requires considerable effort to break aggregates with one hand	Mostly large >10cm and sub-angular non-porous; horizontal/platy also possible; less than 30% are <7cm	Few macropores and cracks	All roots are clustered in macropores and around aggregates				
Sq5 Very compact	Difficult to break up	Mostly large >10cm, very few <7cm, angular and non-porous	Very low porosity. Macropores may be present. May contain anaerobic zones	Few roots, if any, and restricted to cracks				

Image credit: SRUC, Scotland's Rural College.

Measuring the hydraulic properties of soil (their ability to store and conduct water) enables us to understand the availability of soil water for plants and to quantify drought and flood risk at a given site.

Soil compaction assessments

Compaction of soil is correlated with the penetration resistance of the soil, when all other factors (for instance water content) are held constant[173]. Penetration resistance of soil can be obtained using penetrometers, which measure the force required to push a probe through the soil at a constant speed[174]. Penetration resistance is a good predictor of soil porosity and the ease with which roots can penetrate soil[175]. However, the relationship between penetration resistance and plant growth can be complicated to predict as it depends on soil type and properties such as soil moisture, as well as the plant species[176]. For example, in one study the root growth of soybean plants was restricted at half the soil penetration resistance value that affected cotton plants[177].

The bulk density of soil is also used for assessing soil compaction, and it further affects soil porosity, water content and thermal conductivity[178]. Bulk density is the weight of soil in a given volume and can be measured in multiple ways[179]. The most commonly used method is the inexpensive 'core method', where soil samples are collected using a volumetric cylinder, the mass measured, then the sample dried at 105 °C for 2 – 3 days depending on size and moisture content, and then the mass of the dry soil sample measured and soil bulk density estimated[180]. Whilst still requiring some expertise, samples can be collected by land managers provided they have a suitable volumetric cylinder and an understanding of how to correctly sample their field. These samples are then sent for analysis by agricultural soil scientists and soil consultancies who perform the measurement at a low cost per sample. Different soil depths can be sampled but the technique is destructive and, for an acceptable level of accuracy, 25 samples per field should be taken, making sampling a time-consuming process[181]. However, if this were used at a wider scale purely for tracking change in soil properties over time, it would require fewer samples per field.

As with measures of soil penetration, bulk density values can be highly variable, and they are affected by a multitude of variables including soil clay content, carbon content, and climatic conditions[182]. More sophisticated measures of bulk density are being developed. One example is the indirect radiation method, a non-destructive, field-based method that measures the path of gamma rays through soil[183]. It is rapid, providing results in approximately 15 minutes, but can cost thousands of pounds for a field to be scanned and requires high operator experience. However, measurement accuracy with this method decreases with soil depth, limiting the application to soil layers approximately 0 – 15 cm thick[184].

Soil water assessments

Measuring the hydraulic properties of soil (their ability to store and conduct water) enables us to understand the availability of soil water for plants and to quantify drought and flood risk at a given site[185]. Similar to bulk density, there are a number of methods of varying degrees of complexity that can be used. The infiltration rate of water into the soil can be measured using an infiltrometer. There are different types of infiltrometer but all involve driving a ring into the soil and then supplying water into the ring, then monitoring the rate at which water infiltrates the soil. A basic single ring infiltrometer is shown in Figure 10.

The infiltration rate is calculated from how quickly the water enters the soil, typically using an equation developed by Zhang[186]. Infiltrometers are simple to use but can be time consuming to calibrate[187]. Modelling can also be used to describe the hydraulic properties of soil based on easily measured data. Data from many researchers are compiled in soil databases, allowing soil properties such as water retention and conductivity to be predicted in cases where actual measurements of the soil are not possible[188].

Soil remote sensing

Remote sensors collect data about soil properties by detecting the energy that is reflected from Earth, and can use optical (encompassing ultraviolet, visible and infrared frequencies), radar (radio waves) or LIDAR (Light Detection and Ranging) sensors[189]. These sensors can be mounted on satellites, on aircraft or even on unmanned aerial vehicles (drones – see Figure 11) and measurements performed in the field[190]. The advantage of remote sensing is that it is non-destructive and can provide data on any scale, be it local, regional or global[191].

The advantage of remote sensing is that it is non-destructive and can provide data on any scale, be it local, regional or global.

FIGURE 10

A single ring infiltrometer.

Source: https://en.wikipedia.org/wiki/Infiltrometer

Remote infrared sensing for the measurement of soil organic carbon concentration is becoming increasingly available.

LIDAR can accurately estimate soil surface roughness (a representation of soil surface variability useful for modelling surface water flow and sediment/nutrient transport) to within 0.8 cm[192]. Remote infrared sensing for the measurement of soil organic carbon concentration is becoming increasingly available[193]. High-resolution data obtained from soil samples under laboratory conditions can serve as a 'gold standard' for comparison against data collected remotely. Remote sensing offers a level of detail and spatial scale that is not possible with the use of point measurements alone[194]. However, data acquisition using remote sensing to measure soil structure can be hampered by vegetation and cloud cover[195] and on-the-ground data collection is required to maintain the reference databases[196]. Remote sensing has mostly been used by scientists but the costs are decreasing enough that soil consultants are also beginning to offer it as a service to land owners.

FIGURE 11

Unmanned aerial vehicle (drone) and sensor[197].

Modelling

Over the past few decades, mathematical models have been developed by scientists for a range of different soil structure measurements including soil carbon[198] and soil moisture[199]. Models can be a powerful and low-cost method for describing natural systems and informing decisions that affect a variety of sectors. Models can combine multiple pieces of information to generate an overall rating of soil quality. For example, Hassall and colleagues defined a model that combined expert opinion with real world data to quantify soil quality and health, including good soil structure[200].

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[201,202]. Past comparisons of field experimental data and modelling exercises have demonstrated the variation in outcomes between different models and demonstrate the significant levels of testing and calibration with empirical field data that is required for models to be useful for decision making. There are moves to develop a new generation of soil models based on a systemic approach comprising relevant physical, chemical, and biological processes to address critical knowledge gaps in our understanding of soil processes and their interactions[203]. This is a very active area of research, with many new models constantly becoming available[204]. However, the use of models can be daunting to non-experts. An app or easy to use interface would be required to enable non-experts to use such models for soil management or monitoring purposes.

Over the past few decades, mathematical models have been developed by scientists for a range of different soil structure measurements including soil carbon and soil moisture.

Interventions

Cover crops can improve nutrient levels, increase nitrogen levels in the soil, improve soil structure, reduce parasite pressure, prevent weed growth, and increase soil and other terrestrial biodiversity.

This chapter explores some of the possible interventions that farmers and land managers can take to improve soil structure. It is not always straightforward to translate a measurement into the best course of action. Furthermore, the financial and time pressures on farmers to sow their crops each year means that the time available for the soil to recover, either naturally or through intervention, can be short. There is no 'one-size-fits-all' approach, due to the variations in climate, soil and crop type across the UK, and not considering local variations could result in detrimental courses of action.

Interventions to minimise soil erosion and degradation

In agriculture, the fallow period is the period between the harvest of one crop and the sowing of the next crop (Figure 12). Depending on harvesting and sowing dates, the fallow period can range from several days to up to nine months. During this period, the soil is potentially left with reduced plant cover. Bare soil is vulnerable to water and wind erosion which can adversely affect soil quality by reducing soil infiltration rates, water-holding capacities, nutrient content, organic matter and soil depth, especially in the event of a long fallow period. It is necessary in England under cross-compliance guidelines to provide minimum cover for soil, even during the fallow period, for instance by providing cover with crop residues[205].

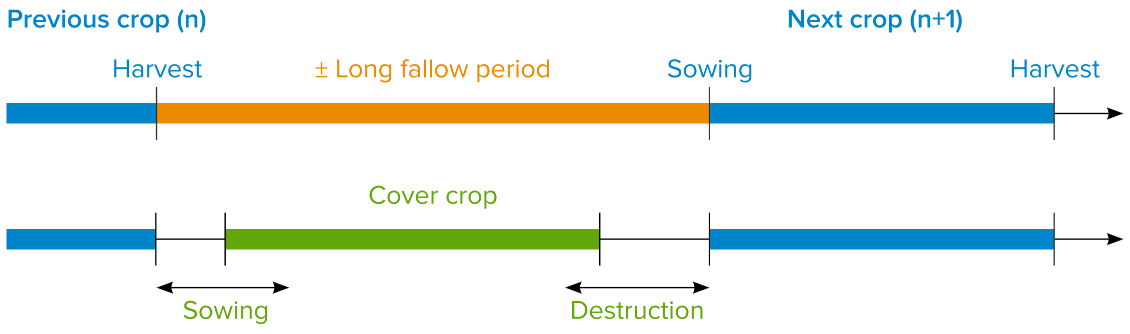
Cover crops

One way to reduce soil degradation is to cover the soil with a crop during the fallow period. Cover crops, sometimes called catch crops or green manure, are crops that are not planted to be harvested but are destroyed (or their growth is stopped) before the main crop is planted.

These cover crops can improve nutrient levels (through reduced erosion and slow release of nutrients when the cover crops decay), increase nitrogen levels in the soil, improve soil structure, reduce parasite pressure, prevent weed growth, and increase soil and other terrestrial biodiversity[206,207]. The biomass of cover crops is returned to the soil, thereby providing organic matter for the next crop and improving the fertility of the soil[208]. However as cover crops are not harvested for profit, the efforts required to sow and then destroy them, plus the upfront cost of the crop itself can be discouraging, even if in the long term the improvement in the soil and subsequent main crop yield offsets this loss.

FIGURE 12

Diagram showing the fallow period in an annual crop rotation (top) and the planting of a cover crop during this period (bottom)[209].



Source: INRA 2012.

'Leys', or short-term rotations of grasses and legumes in place of crops, have been traditionally used to restore soil structure following a crop season.

Field margins, leys and small field wetlands

Hedgerows, grasses or legumes (with nitrogen fixing properties) can be grown in field margins to reduce erosion and nutrient transfer between fields or into water courses. A recent study found that the soil beneath both hedgerows and grassy field margins has better structure, reduces flood risk, enhances soil carbon storage and increases the soil biodiversity across agricultural landscapes[210]. The planting of broadleaf trees has been shown to reduce soil surface runoff and increase the rate of water infiltration into the soil[211].

'Leys', or short-term rotations of grasses and legumes in place of crops, have been traditionally used to restore soil structure following a crop season. Clover-grass leys have been shown to improve soil structure, with one study showing that soil bulk density decreased and organic matter content increased in one year relative to surrounding arable soil[212]. Leys have been shown to reduce the level of erosion on arable soil[213]. Ley rotations have also been shown to recover earthworm numbers, which help to further improve soil structure[214].

The construction of small field wetlands along runoff pathways can also reduce erosion from fields. Small field wetlands are artificially constructed water bodies, such as lakes or ponds, ideally positioned on unproductive areas of agricultural land and in the path of existing water runoff channels. Their purpose is to slow down and trap sediment and nutrient runoff to allow more time for sediment to build and for nutrients to be taken up by plants or microorganisms. Small field wetlands can also create a habitat for wildlife and sequester large amounts of carbon[215]. However, positioning, constructing and maintaining wetlands requires careful planning and financial input.

Reduced or no-till land management

Tillage refers to turning over the soil to get it ready for planting and is sometimes necessary to remediate compacted soil. It allows weeds to be controlled as well as destroying the shelter and lifecycles of pests (and sometimes beneficial organisms) (Figure 13). Tillage also destroys the mycelial networks (mass of branching thread-like hyphae) of mycorrhizal fungi, which as we have described, can be beneficial for soil stability. Both the weight of the machinery, particularly if not well distributed, as well as the process of tilling itself can be detrimental to the soil structure and enhance soil erosion. As a result, zero tillage (no-till) or reduced tillage (reduced-till) land management can be effective as an erosion mitigation measure, with significantly less soil lost from agricultural fields[216 – 219]. Within a landscape, the long-term use of reduced or no-till farming also strengthens biogeochemical cycling, including increasing levels of soil organic carbon[220] and a number of studies have shown that no-till decreases surface runoff[221,222]. Strip tillage is a type of reduced tillage approach, which disturbs only the portion of soil that is to contain the seed row. Crop residue is removed from the cultivated strips and placed between the rows where the seeds are sown, which has been shown to improve soil structure, protect against soil erosion and conserve soil moisture[223].

The return of crop residues to the soil, an integral component of no-till land management, is crucial to cycling elements such as carbon or nitrogen and reduces the requirement for nutrient replenishment with chemical fertiliser[224]. However, no-till often requires more pesticides and herbicides to be used, which can have an adverse effect on biodiversity[225]. Furthermore, a meta-analysis of no-till versus conventional tillage yields using 678 studies found that no-till land management reduced yields, on average, by 5.1% across 50 crops and 6005 paired observations[226]. The effects of no-till on crop yield are context dependant, for example no-till increases yields relative to conventional tillage systems in arid regions[227]. Thus, switching to no-till land management could be highly beneficial for improving soil structure and increasing some benefits that arise from the soil, but this could be at the expense of other benefits, such as agricultural productivity, and is not suitable for all soil types or weather systems. Issues such as weeds, pests and soil compaction mean that it is import to meet these needs at the farm level.

FIGURE 13

Example of a field being tilled.

© Murika.

Interventions to mitigate soil compaction

The rate of soil recovery from compaction can be slow and depends on the soil type, degree and depth of compaction, and climate[228].

Natural soil recovery from compaction

Soil can recover from a certain amount of compaction with no manual intervention. 'Natural recovery' of soil from compaction occurs via wetting and drying cycles, freeze-thaw cycles, and disruption of the soil by animals and plants, such as earthworm burrowing and root penetration and decay[229]. However, this is only effective for lightly compacted soil, for example due to damage from intermittent cattle grazing[230]. Dry, coarse grained soil has been shown to be able to recover within a year[231], whereas sandy soil has been shown to recover more slowly, sometimes taking as long as 40 years to recover after the last compaction event[232] and severely deteriorated soil can take up to 190 years to fully recover[233].

Dry, coarse grained soil has been shown to be able to recover within a year, whereas sandy soil has been shown to recover more slowly, sometimes taking as long as 40 years to recover after the last compaction event and severely deteriorated soil can take up to 190 years to fully recover.

The effectiveness of earthworms to reverse compaction depends on many parameters, such as the weather and activity of other organisms which may impair the effectiveness of the introduced earthworms through competition and/or predatory interactions.

Manual interventions for compacted soil

Earthworms are excellent 'ecosystem engineers' and are frequently included as an indicator of soil quality. Due to this, there has been interest in releasing earthworms into compacted soil to aid recovery. Artificial breeding of earthworms is required to allow enough earthworms to be added into the soil to be effective at improving it. This process is not always feasible for native species due to the difficulty in fine-tuning conditions such as moisture content, food content and light regimes for each species[234]. For this reason, and because they can tolerate a wider range of physical, chemical and climatic conditions than native species, exotic, and sometimes 'invasive', species are sometimes introduced which leads to other environmental problems such as threats to local biodiversity[235].

The effectiveness of earthworms to reverse compaction depends on many parameters, such as the weather and activity of other organisms which may impair the effectiveness of the introduced earthworms through competition and/or predatory interactions. As a consequence, the potential of earthworm introduction to promote the rehabilitation of compacted soil remains limited[236].

Another intervention to promote the recovery of compacted soil is 'soil aeration', which is the perforation of the soil with small holes to allow air, water and nutrients to penetrate. However even when performed with tractor-mounted or towed mechanical 'aerators' it is time-consuming and if carried out in the wrong conditions (eg on wet soil), can lead to further deterioration or re-compaction. A range of mechanical methods are available to improve damaged soil structure including topsoil lifting, ploughing and subsoiling depending on the degree of damage and where it occurs in the soil profile. Where the compaction is found on the surface or in the topsoil, surface tillage may be sufficient, but deeper treatment, for instance the use of deep rotary-tines (prongs) may be required where compacted areas form below topsoil[237]. However, machinery traffic itself can cause major problems to the soil (Figure 14) due to compaction of soil by the wheels of tractors, trailers and harvesters, with the area subjected to traffic often exceeding 40% of the total cultivated field area[238].

FIGURE 14

(a) Soil erosion in field caused by surface runoff of rainwater[239].

(b) Ruts formed after the passage of vehicular traffic on soil; an example of compacted soil[240].

Controlled traffic farming (CTF) can help to limit the damage caused by agricultural traffic. This is a land management technique often used in precision farming, where all field traffic is supported on permanent lanes and crop growth is on non-trafficked, wide beds[241]. Global Positioning Systems (GPS) are often used to steer the machinery and keep it on a precise track thus confining compaction to the permanent wheel tracks only. This results in more porous soil overall and therefore greater penetration and movement of water, air, plant roots and soil organisms which helps improve biodiversity and water filtration, in addition to increasing agricultural productivity[242,243].

However, CTF requires farmers to commit to a long-term and potentially expensive change in their machinery due to the requirement to match the track widths (the distance between wheel centres on the same axle) of all field machinery. The dependence on satellites for GPS also introduces the risk of technological interruptions to the farming schedule. Finally, although the condition of the majority of the soil in the field will improve, there is increased erosion and compaction risk under the permanent wheel tracks which may result in gullies developing (Figure 14), especially if the field is on a slope. Thus, CTF may not be appropriate for all farms and land managers particularly in upland systems.

This chapter has explored the interventions available to improve soil structure. However, while some interventions have multiple benefits, for example cover crops are beneficial to both biodiversity and agricultural productivity, there can also be trade-offs. Some trade-offs relate to financial and time or scheduling pressures on farmers. Others relate to the benefits that a farmer or land manager can choose to deliver simultaneously. For example, choosing whether to till the land, which can result in long-term soil structural damage, but less pesticide and herbicide use, or choosing a no-till management regime which may be beneficial to soil structure and soil carbon content but potentially result in lower yields in the short-term. Trade-offs such as these need to be considered when creating policy to promote well-structured soil. This is explored in further detail in the next chapter.

Discussion

This synthesis has demonstrated the various links between good soil structure and the benefits it provides, in terms of biodiversity, agricultural productivity, clean water and flood prevention and climate change mitigation. These findings are summarised in Box 5.

BOX 5

A summary of the key findings regarding the benefits associated with soil structure

Biodiversity
The soil biological community and soil structure are closely linked; soil structure influences the type and activity of soil organisms, while soil organisms affect the physical structure of the soil. In addition, soil biodiversity, and its associated influence on soil structure, directly supports other terrestrial biodiversity and contributes to a range of ecosystem processes such as: nutrient cycles; soil formation; the control of plant, animal, and human pests and diseases; and climate regulation.

Agricultural productivity
Studies have shown that good soil structure is correlated with higher grain yields[244]. Compacted soil often results in a decrease in crop yield due to detrimental effects on the crop's root system. Indirectly, a well-maintained soil structure can also enhance crop productivity through providing a habitat for earthworms.

Clean water and flood prevention
Soil can be seen as 'natural flood prevention infrastructure'[245]. Good soil structure leads to increased infiltration of water into the soil and also to increased water storage via uptake into root systems. The degree to which soil can contribute to flood prevention is strongly reliant on it being well-structured. Furthermore, when water flows over compacted soil, this can increase the erosion of topsoil and the pollution of freshwater systems.

Climate change mitigation
Differences in land management can affect the extent of soil carbon sequestration. Many interventions which have been suggested to increase soil carbon levels, such as reduced and no-till regimes or the use of cover crops, also improve soil structure and so deliver additional benefits.

There are a huge range of soil types in the UK. Overlaid on these could be the range of different altitudes, habitats and farming systems found across the UK. Designing a policy framework which allows for this complexity and context specificity is likely to be very challenging.

Alongside the benefits, this synthesis has explored the interventions that a farmer or land manager can take to improve the structure of their soil and the relationship between these interventions and the beneficial outcomes is described. Interventions include moving from a till to no-till or reduced-till regime, planting cover crops, controlled traffic farming and adding organic matter to soil. There is a strong body of scientific evidence that links many of these interventions with improved soil structure, and associated benefits.

Many of the benefits from soil structure that we have described here can be delivered in parallel, with interventions to improve soil structure leading to increased yield, enhanced biodiversity, higher soil carbon levels and improved water holding capacity. These can be termed ‘multiple benefits’. However, there are some trade-offs in terms of prioritising one of these benefits above others. For example, no-till approaches to reduce runoff and improve water holding capacity may result in the farmer using more herbicides for weed control, which could have a negative effect on biodiversity or increase freshwater pollution, and would not be possible for an organic system.

One of the major challenges for land use policy is that beneficial interventions and optimal land management are very context and site specific. This is certainly true when managing soil. There are a huge range of soil types in the UK. Overlaid on these could be the range of different altitudes, habitats and farming systems found across the UK. Designing a policy framework which allows for this complexity and context specificity is likely to be very challenging. Soil management frameworks need to be flexible enough to allow farmers and land managers to optimise the range of benefits delivered by a range of soil properties and minimise trade-offs. If incentivised correctly, good soil management (including for good soil structure) can be both economically beneficial for the farmer and more widely beneficial in terms of providing ecosystem services and ecosystem benefits. A shift in mindset towards multiple benefits and multifunctional land use may be required to achieve this.

For example, on sloped land, it may be most sensible to focus on improving the water holding capacity of the soil and integrate buffer strips to reduce runoff, therefore improving water quality, reducing soil erosion and reducing the risk of flooding. In many instances, multiple benefits will go hand-in-hand, but we must also recognise the trade-offs. For instance, this decision may be at the expense of planting crops or explicitly focusing on promoting biodiversity. A farmer or land manager may already know which benefits or multiple benefits are likely to be best delivered by their land and will have important knowledge regarding the intricacies of their specific context.

From our conversations, farmers and land managers often know their soil type and take steps to manage the quality of their soil. However, the bulk of the costs of soil degradation occur off-site and will impact neighbours, downstream water users and other ecosystems, and not directly impact the land managers. Therefore, if off-site impacts are not factored in, it can be more economically viable for land managers to exploit the soil in such a way to cause degradation[246]. This synthesis highlights the range of techniques for measuring soil structure and other properties. These range from the semi-quantitative visual assessment of the soil, to the use of satellites to remotely measure soil properties at a global scale.

This large number of options may be overwhelming and the results are often complicated to interpret, even for scientists. A user-friendly interface or app would help land managers access results. In addition, many of these measurement techniques can seem expensive. Therefore, unless farmers and land managers can see the value of this improved understanding of soil structure, in terms of either increased yields and profit, reduced input costs, or in terms of being rewarded for delivering ecosystem benefits, incentivising them to move from simple visual assessment to more complex scientific measures is not likely to be straightforward. In Wales, the government is consulting on plans for a major increase in farmer advice services to help support this[247].

Measures of soil structure which lend themselves to be used as part of a new incentives structure are likely to be semi-quantitative approaches that farmers and land managers can use themselves, are inexpensive and not time consuming. One example of this could involve formalising the visual field assessment of the soil condition using a scorecard. However, it is unlikely for there to be a ‘one size fits all’ technique where a single measure of soil structure is suitable for use in every scenario regardless of soil type, land use and other factors. Therefore, a menu of options, where farmers can pick and choose the most applicable and useful methods to suit their situation seems likely to be best.

A further complicating factor is the variability around outcome metrics for soil structure. Therefore, it can be difficult to monitor when changes to soil structure (for the better or for the worse) have occurred.

Demonstrating a clear, reproducible relationship between land management and the magnitude of change in the associated benefit is less clear from the published evidence. For example, there is a huge range of outcomes for a given increase in soil organic matter[248]. This variability is likely to be due to a combination of soil, crop and climate conditions and how the intervention is introduced. The ability to be able to clearly communicate and link an action with an outcome has implications for soil management and practice, as well as the development of new government policies and reward structures. This variability and non-linear ‘action to outcome’ relationship must be borne in mind if measurements of soil structure are to be used as the basis for any new reward system. As the evidence pathway between action and outcome is subject to many confounding factors outside land mangers’ control, the fair rewarding of outcomes in terms of soil structure could be challenging. Improved training to encourage and enable farmers to monitor soil structure for their own benefit is attractive and could be supported by governments (for example see the Sustainable Farm Scheme[249]).

This variability and non-linear ‘action to outcome’ relationship must be borne in mind if measurements of soil structure are to be used as the basis for any new reward system.

It has been suggested that a helpful measurement or 'soil quality indicator' should[250]:

- Be meaningful, interpretable and sensitive (and measurable) to natural and human-induced pressures and change
- Reflect the desired condition or end point for a particular soil and/or land use and/or function
- Be relatively cheap, practical and simple to monitor
- Be responsive to corrective/management measures
- Be applicable over large areas and different soil/land use types
- Be capable of providing continuous assessment over long timescales

The Agriculture and Horticulture Development Board (AHDB) are working to produce a toolkit to assist with soil measurement and management. The AHDB have trialled a 'soil health scorecard', which brings together the most relevant measures of soil, and once results have been entered into the scorecard, uses a traffic-light system to classify whether investigation (red), monitoring (yellow), or no action (green) is required[251].

Existing soil policy is piecemeal and is made by a wide variety of different policymaking and regulatory bodies, which was highlighted as a major concern in the Environmental Audit Committee's Soil Health Inquiry[252].

Policies and legislation addressing air, water and soil are also sometimes disconnected, with no integrated overview of how these policies interact. It is perhaps interesting to note the EU has now highlighted 'healthy soil and food' as one of its five 'Mission Boards' (alongside cancer, climate change, climate-neutral cities and healthy oceans) in response to this concern[253].

Alongside international and national policy and legislation, industry stakeholders such as supermarkets and water companies promote their own standards and soil management frameworks (Box 1). Organic certification or accreditation to schemes such as LEAF Marque[254] are likely to significantly affect a farmer's decisions regarding how to manage their soil. Multiple 'pulls' may result in farmers having to show evidence of a variety of different interventions, depending on the number of companies that they supply their produce to, which at best may be time-consuming and inefficient and at worst could result in detrimental soil management decisions. Likewise, it could result in confusion and frustration for consumers looking for one clear standard to demonstrate sustainable soil management. Thus, while the drive to improve soil structure and environmental sustainability by multiple companies is to be applauded, much like government policy, it is likely to be most effective for farmers and consumers if standards and guidance are joined up across different sectors.

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.

There are too many variables and uncertainties to predict conclusively the effect of policies on farmer behaviour and soil structure. Instead, the aim is to present plausible, though not necessarily optimal or desirable, future worlds in which efforts are made to improve both the structure of UK soil and the quantity and quality of data collected about it.

It is worth noting that for all of these illustrative examples, the aim is to improve soil structure, but this is just one property of a well-functioning soil. Therefore, by focusing on soil structure here we do not mean to suggest that this should be rewarded above other important properties. In addition, soil structure may be of less functional relevance to different land uses, and reward schemes will have to consider this. For example, different measurements and reward mechanisms may be required if the function of a particular soil is to provide a platform for human activities or store geological and archaeological heritage[255].

Within all of these examples, farmers will need to be able to make informed management decisions based on up-to-date data. It is likely that new technologies, such as drones, satellite imagery and DNA sequencing could aid soil measurement, alongside more traditional soil monitoring methods.

CHAPTER FOUR

ILLUSTRATIVE EXAMPLE 1

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

What: Government policy is developed to improve the way farmers engage with their soil.

How: A semi-quantitative scorecard is designed with input from soil scientists, farmers, agricultural advisers and policy officials. It takes approximately 30 minutes to measure a soil sample and asks farmers to measure their soil using soil quality indicators[256]. Training and guidance on how to perform the measurements and advice on how to interpret the results are included as part of the scheme.

Government incentives are used to encourage farmers to take part. Farmers routinely perform a visual assessment of their soil using the score card and give the soil in each of their fields a score for each of the indicators. These scores are submitted to the government via an app as evidence of participation and in return for this the farmers receive a payment. Note that participation is voluntary and that the payment is not based on demonstrating any change in soil structure or other quality measures but rather for participating.

On the basis of this score, farmers have the option to:

- Do nothing;
- Make a change in land management practices based on their assessment of the soil;
- Make a change in land management practices based on the advice provided as part of the government scheme; and
- Request advice from a soil advisor at their own expense.

Cost to government: Small increase in government spending to receive and process scorecards; Medium increase in government spending to fund training and advice schemes for farmers; Medium increase in government spending to fund incentives (depending on uptake of scheme by farmers) and potentially some level of auditing would be required.

Cost to land manager: Small to medium increase in time required by farmers and land owners to complete the scorecard depending on the number of fields.

Benefits and disbenefits of this approach: This scheme would encourage participating farmers to consider the quality of their soil, and also understand the different factors that are important in maintaining well-structured soil (eg observing if the soil has signs of compaction). By linking how the soil structure looks to a score, this scheme would allow farmers to make informed decisions about how they manage their soil. Additionally, the training and guidance included in the scheme, for example recommending ways to mitigate compacted soil, may allow soil to recover and improve. This would have wider benefits for farmers but also for other users of the land. Finally, by submitting these scores to Defra, it would allow a database, albeit a largely non-quantitative one, of the health of the UK's soil to be compiled which may prove useful in designing future soil policy and for monitoring longer term trends.

On the other hand, by asking farmers to perform the measurements without external expertise, there may be inconsistencies in how the data is collected. Additionally, there would also be a risk that any generic guidance provided to farmers as part of this scheme would not consider the variability of soil types and land uses. If the farmer misinterprets how to perform the measurement, and therefore obtains an incorrect score for their soil, at best this may result in no positive outcome, but at worst it could lead to a farmer performing unnecessary or even harmful interventions due to misunderstanding how to interpret the results or following guidance that is incorrect for their particular soil. There is also a risk that if participation is voluntary, only farmers who are already conscientious about their soil management would take up the scheme, and not perhaps the ones who most need to improve, limiting its effectiveness.

To mitigate these risks, it would be important to ensure the methods are sufficiently easy to administer and to implement a quality training, support and mentoring scheme alongside this. It might also be important to include some element of quality assurance, where the accuracy of measurements is tested by comparing farmer scores to expert scores on an agreed sample of farms.

CHAPTER FOUR

ILLUSTRATIVE EXAMPLE 2

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

What: A government policy for establishing a scientifically rigorous monitoring scheme for the UK's agricultural soil is developed.

How: A set of scientifically rigorous soil quality indicators are designed and data are collected by soil scientists from randomised farms as part of a government-run soil monitoring scheme. Samples are taken at regular intervals and the information is used to create an informed map of the health of the UK's soil, and analysis performed so that government can understand how best to prioritise future incentives to gain further benefits from the UK's soil. Farmers are informed of the results of measurements taken on their farm, and given recommendations and support for changes to land management practices for their consideration, though implementing these recommendations remains optional.

Note that there is the option to expand an approach like this into a national monitoring scheme which goes beyond farms and tracks, in a structured and unbiased way, the soil quality of the UK, by habitat, region and soil type. But this goes beyond what we are describing here.

Cost to government: High. This would require new infrastructure to:

- Design scientifically rigorous soil quality indicators that reflect the benefits that could be gained from the soil;
- Engage and enrol farmers onto the scheme;
- Employ and train soil scientists in how to perform the soil sample collection, measurement and analysis including identifying soil that would benefit from a change in land practice; and
- Deploy independent advisers as part of an advisory service to support farmers to make the right decisions from the array of options.

Cost to land manager: Minimal. It requires providing access to soil scientists and permission for samples of soil to be taken.

Benefits and disbenefits of this approach: 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. The data could be used by policy officials to identify opportunities for meeting their environmental commitments, such as fields that could be good candidates to target for improved carbon sequestration to help achieve net zero.

It could also be used to identify fields that are currently vulnerable to surface runoff and flooding and therefore would benefit from interventions to improve soil structure or a change in land use. Likewise, the database could be used to identify any upward or downward trends in the benefits that soil provides and inform the development of future scientific models and national maps of flooding and other risks.

Due to the rigorous and scientific nature of this option, participation would be randomised and not optional. However, farmers would need to be willing to let scientists access their land to take measurements. Therefore, getting farmers to engage and see the process as beneficial for them would be vital. Again, this would require good support, training and mentoring so that farmers and land managers can benefit fully from the results. Farmers may be concerned that these results would lead to negative penalties, such as fines or reputational damage, and so the purpose of these measurements (along with who would own and have access to the data) would have to be very clearly and carefully communicated to the sector.

CHAPTER FOUR

ILLUSTRATIVE EXAMPLE 3

New regulation, including incentives and penalties.

What: New regulation is introduced that incentivises and/or penalises the way that farmers and land managers manage their soil.

How: The structure of the soil is measured and monitored by soil scientists or qualified soil advisers, belonging to a government regulator on a five-year rolling basis, recognising that soil can take time to respond to changes. In the short term, payments could be made on the basis of good management, however after five years and once measurements have been taken twice, payments could shift to being based on good soil quality outcomes.

On the basis the measurements collected and what is feasible or expected given the soil type and land use, the soil in each field could be given a rating, eg outstanding, good or requires improvement. Farms whose soil is judged to be 'outstanding' are given a financial reward from public funds. Farms with soil that 'requires improvement' do not receive a financial reward and are given additional advice and support to help improve the condition of the soil. These less well performing farms could also be visited more frequently.

A 'requires improvement' score gives farmers the option to:

- Do nothing;
- Make a change in land management practices based on their own assessment of the soil;
- Make a change in land management practices based on the advice provided as part of the government policy; and
- Request advice from a soil agency at their own expense.

A government loan might be available to help facilitate any changes that would be required.

If the soil has not shown improvement within five years of the first 'requires improvement' score, there is an option to restrict the payments that the farmer is eligible to for.

With this model, there would also be the option to have the soil quality rating linked to some kind of trademark or certification, which could be used on the private market to demonstrate a higher standard of environmental management. Alternatively, these measurements could be incorporated into existing certification schemes, given the large number that already exist.

Cost to government: Very high. This would require new legislation, the establishment of a new regulator or an expansion of the remit and staffing of an existing body (eg the Environment Agency or Natural England). It would also require the training of many soil samplers, incentive payments for outstanding soil, support and training for farmers, and possibly funds for farmers to deliver improvements.

Cost to land manager: Medium. If their soil is found to require improvement, farmers and land managers would not receive public money for this. Further costs may also be incurred if they cannot or would not improve their soil by the five-year deadline, as they may no longer be eligible for other public funding.

Benefits and disbenefits of this approach: In this example, the scheme requires all farms to take part, therefore the measurements of the soil would not be subject to the sampling bias identified in Illustrative example 1. However, by providing funds to farmers for good practice in soil management and not rewarding bad practice, there still remains an optional element to this approach in terms of whether to act on the results. Farmers may therefore be dis-incentivised to monitor their soil if they were not targeting this as a particular source of income.

Any new regulatory powers would have to be very carefully introduced as 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. Furthermore, farmers may not be able to improve their soil sufficiently over five years to raise the soil standard to 'good', perhaps because they do not have the resources to, say, switch to controlled traffic farming to minimise compaction, or build small wetlands to reduce erosion into waterways although a government loan could be offered to help with this. The scheme would also have to be designed as to not penalise farmers experiencing severe weather extremes.

Extending this approach to include the measurements within a 'trademark' or certification scheme has the potential benefit of using market forces to incentivise and penalise farmers by altering market demand for their produce. However, it must be recognised that there is already a large number of certification schemes on the market and it may be sensible to work in collaboration with existing schemes as opposed to inventing something entirely new.

The regularity of monitoring and assessment would also have to be carefully considered, accounting for the amount of time it takes for soil management interventions to be effective. Five years is just given here as an arbitrary period in which to do this.

ILLUSTRATIVE EXAMPLE 4

Maintain the *status quo*

What: Soil policy continues to be split across multiple policies, and policy frameworks do not result in a unified approach to measuring and monitoring soil quality. Interested parties such as supermarkets and water treatment companies, and advisers from soil accreditation bodies such as LEAF and Soil Association, continue to incentivise and advise farmers and land managers on the best way to manage soil to support their own priorities.

How: There continue to be limited incentives for farmers and land managers to engage with their soil or measure and record soil structure and its benefits.

Cost: No increase in spending, time or staffing by government or land managers.

Benefits and disbenefits of this approach: Some farmers are already managing their soil to a high standard, yet without a national database, the overall picture of soil management and quality in the UK is unknown. Additional services provided by other interested parties can be helpful to farmers, such as providing training and incentive programmes (eg Nestlé) or soil guidance (eg ASDA's collaboration with LEAF), particularly as they are produced at no cost to the taxpayer. On the other hand, without a formal mechanism for understanding and monitoring soil, opportunities to meet current or future government targets, legislation or even reduce government spending overall can be missed. Additionally, for those farms who are not managing their soil optimally, the risk of not introducing a soil specific policy is that over time the soil would degrade to the extent that it results in yield losses and increased costs to farmers and wider society, and eventually result in functionally redundant arable land in the most degraded areas.

Annex 1: Acknowledgements

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Annex 2: Methodology

Question setting

Initially, a mapping of priority policy areas led to the identification of soil as a broad topic of interest. We then conducted desk-based research and consulted with Royal Society Fellows and key policy stakeholders.

To refine the topic focus, we hosted two workshops with subject experts from academia, NGOs, government and industry. The first, held at the Royal Society on 28 March 2019, was facilitated by URSUS, a specialist facilitation agency. The second was held on 11 July 2019 by Royal Society Staff.

Attendance lists can be found in Annex 1: Acknowledgements.

Literature review

To gather academic literature, the team commissioned an information specialist to perform searches of relevant databases using a search strategy devised in conjunction with the Royal Society team.

Search terms were run on three different databases: CAB Abstracts (Ovid), Web of Science and Agris (via Ebsco Discovery). These searches were conducted in August 2019. Two searches were conducted, the first search targeted primary academic papers and was geographically limited to countries in Western Europe (Netherlands, Germany, France, Ireland, United Kingdom) and returned 830 results. The second search targeted review papers and was not geographically limited and returned 479 results. For both searches results were limited to papers published since 2010. Full search terms are available on the Royal Society website as supplementary information.

Following the search, all articles were screened for inclusion based on reading their titles and abstracts. Initially, the screening process was trialled on a small sample of articles by the whole team and following this, each study was then screened by one member of the team. In cases where team members were uncertain of the inclusion of an article, these articles were highlighted for discussion and reviewed by 1 – 2 other team members. This screening process resulted in a total shortlist of 208 studies. Where appropriate, further studies cited by the articles in this body of literature were also added to the shortlist, with no restriction on the publication date.

The full text of all papers in this shortlist was reviewed and details entered into an extraction table capturing information on the following:

- Bibliographical information on the article
- Type of data used
- Information on the history or current policy relating to soil management
- Country or regional focus
- Soil type
- Evidence of public benefit outcomes related to soil functions
- Techniques or metrics used to measure soil functions
- Discussion of soil management interventions, including who could perform these
- Article quality and relevance

The extraction template was also piloted for a subset of articles by the whole team. Extraction was then conducted, with each article reviewed in detail by one member of the team. Additional relevant literature was suggested during key informant interviews, focusing in particular on grey literature and policy documents which were also reviewed.

Analysis and review

To analyse and combine the information an internal staff workshop was held to review the preliminary findings and finalise a structure for the evidence synthesis report. Each section of the synthesis was assigned to a member of the team, who reviewed the extracted data from the studies and summarised key findings. These findings were then written up, with further reference back to the papers cited where necessary. The overall messages, focus and evidence gaps that constitute the discussion section were discussed with the team, and written up by a team member. Each section of the synthesis was reviewed by at least three other team members to ensure accuracy and completeness. The synthesis was subsequently sent out to the FRS lead Alastair Fitter, a policy specialist and expert reviewers (Annex 1).

Limitations and caveats of the evidence synthesis methodology

This study is subject to a number of important caveats and limitations, including the following:

1. The literature review was a rapid evidence assessment rather than a systematic review. This means we did not cover all possible literature. However, the review included a diverse set of carefully selected articles, informed by expert guidance, and therefore paints a wide-ranging picture of the state of play with respect to soil structure and the benefits it can provide.

2. We have not been able to reflect the full complexity of the literature in this overview synthesis. The aim of this synthesis is to provide a concise, policy-relevant overview of the key issues and evidence. Inevitably, there are many details and nuances that could not be included given the scope and length of this study.

3. We have consulted with and hosted workshops for key experts in the field, from a range of academic, policy, industry and NGO perspectives. However, we only spoke to a sample of individuals working in the field; therefore, the information provided may not be representative of all researchers in the relevant fields, or the full range of work conducted (particularly in an international context).

Limitations and caveats of the methodology specific to this soil structure evidence synthesis

4. We have deliberately focused this synthesis predominantly on agricultural soil. The relationship between soil structure and benefits for other land uses such as urban soil, forestry, wetlands, peatlands and heathlands and others may be different.

5. The majority of academic literature was relevant to the UK, Netherlands, Germany, France, Ireland based on advice by our lead Fellow and academic literature[257]. The majority of policy was relevant to the UK.

6. At the time of writing this synthesis, in England, the Agriculture Bill was laid before the UK Parliament (January 2020) and was progressing through the House of Commons. The Bill had been amended to include “financial assistance for or in connection with… protecting or improving the quality of soil” and an Environmental Land Management scheme was being developed based on ‘public money for public goods’. However, there remained uncertainty around exactly how incentivising good soil management will be expressed in policy going forward. We hope that despite this ambiguity, the reflections and findings contained in this synthesis will be useful to policy makers considering future agricultural policy in all four UK nations.

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