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Restoring Agricultural Soils

Changes to the management of agricultural soil could contribute to improving the ability of soils to produce crops, as well as to wider benefits including mitigating future climate change. This POSTnote summarises the state of England's agricultural soils and evaluates soil stewardship opportunities. Soil indicators that could be used for monitoring in policy frameworks and incentives relating to soil restoration are explored.

Overview

- Intensive agricultural practices have caused soil degradation in the UK, leading to loss of carbon, nutrient imbalances, erosion, compaction, and contamination.
- Key soil indicators, such as soil organic carbon, have decreased. This is affecting the benefits soils provide, such as food production.
- Research provides evidence for practices that could be used to reverse soil degradation in different contexts. Examples of practices include cover cropping and biochar additions.
- The 2022 Sustainable Farming Incentive scheme will pay farmers to manage soils, but it is not clear that the level of payment is great enough to incentivise change.
- Innovations in soil monitoring technology could simplify national and farm scale soil monitoring, reporting and verification.

Background

Soils underpin the food system, providing nutrients and water for plants to grow,[1,2] as well as other benefits including carbon storage and water regulation. The components of soil are minerals, organic matter, organisms, water and gases.[3] Soil Organic Matter (SOM) is the organic material leftover from decomposing plants and animals, whereas Soil Organic Carbon (SOC) is the measurable carbon concentration of SOM (PN 502).[4–6] A productive soil for agriculture has a balance of nutrients (such as carbon, nitrogen and phosphorous) and minerals, for example, calcium and zinc, as well as appropriate SOM content.[7,8] Soils are a highly integrated and complex system of ecological processes that provide functions and services to wider ecosystems.[9–13] Soil functions can include productivity, water and nutrient cycling, carbon sequestration and habitat provisioning (PB 26). These functions relate to services (e.g., food production, water quality, climate regulation and biodiversity).[9] Dependent on the main land use, such as food production or flood prevention, soil management seeks to optimise different functions to increase resilience (Box 1).

In the UK, agricultural land comprises 71% of the total land area[14] and the agriculture sector contributes roughly 10% of greenhouse gas (GHG) emissions.[15] Cropland soils are more heavily depleted of SOC than grasslands having lost 40 to 60% organic carbon as carbon dioxide (CO_2) under intensive management.[16] Grasslands are estimated to store 64.6 tonnes of carbon per hectare (t C ha) in the top 15cm of soil, whereas croplands are thought to only store 43 t C ha.[17,18] Degradation of soils by poor management practices and climate change could be reversed by restoration. The Climate Change Committee's (CCC) third *Climate Change Risk Assessment* (CCRA3) report (2021) outlines key evidence for growing climate risks to soil in the future, including heavier rainfall, increasing erosion and compaction.[19] The UK Government's Soil Health Action Plan for England will 'address the challenge of increasing soil degradation, supporting the 25 year environment plan ambition for sustainable soil management by 2030'.

Benefits from soils

Soil systems contribute several benefits to humans and the environment:

- **Food production**: It is estimated that 99% of food crops consumed were grown in soil.[20] In 2019, agriculture contributed £10.4 billion to the UK economy and roughly

Box 1: Key terms for describing soil states
The terminology used to describe the state of a soil is often used interchangeably in policy:
- **Soil health** is defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans".[9] Biological components are often linked with soil health (PN 601).
- **Soil quality** is more often associated with the fitness of a soil for a specific function and is determined largely by physical and chemical characteristics.[21]
- **Soil security** is a more novel term relating to provision of ecosystem benefits (such as water quality) and soil as a public, rather than private, good (PN 557).[22]
- **Resilience** is complex but can be described as the ability to withstand shocks and disturbances (PN 543). Soil resilience is largely determined by soil health; efforts to improve soil health will help buffer against future shocks (such as the ability to continue producing food under a changing climate).[23–25]
- An alternative concept is a **One Health** approach, a holistic concept of linking environmental (physical and chemical soil properties) and organismal (plants, animals and humans) health, and the services and functions provided (PB 42).[26,27]

55% of food consumed in the UK was produced domestically.[14]
- **Water regulation**: Uncompacted soils allow water to infiltrate, reducing surface runoff and freshwater leaching of nutrients (PN 661) during wet weather. Soils also retain water for plants during drier periods.[28]
- **Air quality**: Soil-air interactions are important for the growth of plants, which are linked with and regulate below ground microbial processes, but soils can also be sources of pollutants, such as the GHGs nitrous oxide and methane.[29,30]
- **Biodiversity and habitat**: One gram of soil contains tens of thousands of microbial species, dominated by bacteria and fungi (PN 601).[31,32] Soil also provides suitable habitat for many macro-invertebrates, such as earthworms and bee species, and habitat and resources for vertebrate species, such as moles. Biodiverse soils can support complex food webs in farmland systems and increase yields.[33]
- **Carbon storage**: Grasslands in the UK are estimated to store 32% of national topsoil SOC.[34] Although arable soils have a lower capacity for carbon storage due to annual cropping disturbances, they account for 12% of the topsoil SOC stock in Great Britain.[18,35] Soils also lose carbon as CO_2 during respiration, which can be greater under intense synthetic fertiliser use due to increased microbial activity.[36,37]
- **Nutrient cycling**: Key nutrients are recycled within soils contributing to plant growth and atmospheric conditions. Plant litter decomposition leads to carbon and nitrogen inputs to soil.[38]

The state of soils
There is roughly 9.2 million hectares of agricultural land in England, of which 52% is arable (including uncropped arable land and temporary grassland) and 36% is permanent pasture.[39] Historically, the typical farming system of the UK was mixed, both arable and grassland. This ensured a circular system, where waste from one part of the farm (manure and straw) could be used elsewhere on-farm (as fertiliser and feed or bedding) (PB 42). England's current agricultural systems follow a rough East/West divide, with mostly arable farming in the East and pastoral farming in the West, owing to climate and soil differences. Peatland soils are found largely in the uplands, but also in the lowlands (such as the East Anglian Fens) where they are important for horticulture but also a major source of GHG emissions (PB 42). Intensification of agricultural practices after the Second World War included an increase in mechanisation, the removal of field boundaries to create bigger fields, such as hedgerows, and increased use of synthetic fertilisers and pesticides (PB 43).[40] The consequences of these were loss of soil, changes to soil structure and chemistry and a loss of soil biodiversity.[41–44] Despite a lack of comprehensive monitoring before and after these changes, there is evidence of long-term deterioration on the overall state of soil.[45–49]

Pressures on soils
- **Nutrient status:** The nutrient content of soil differs depending on land use and management. Growing crops consistently decreases the nutrient status of soils, resulting in a need to increase additions of artificial nitrogen and phosphorous to retain productivity.[16]
- **Erosion:** Soils form over long timescales. For example, a millimetre of soil can take around 20 years to form.[48] However, soils can be eroded rapidly through wind and water and roughly 2.9 million tonnes of topsoil are eroded in England and Wales annually.[50] Erosion risk is greatest for peatland soils in drier years and poorly managed soils under heavy rainfall.[4] Loss of soil can result in carbon losses to the atmosphere as the GHG carbon dioxide (CO_2), as well as nutrient losses to waterways (PN 661).[20,48,51]
- **Compaction:** 3.9 million ha of agricultural land in England and Wales are at risk of compaction, with increased risk for heavy clay soils in wet periods.[50] Heavy machinery and intensive grazing increases soil compaction, compressing the soil structure and reducing porosity (air spaces), nutrient cycling and gas exchanges, limiting productivity.[44,52] Compacted soils are more likely to become waterlogged, increasing surface runoff intensity, affecting flood risk (PN 623), and increasing nitrous oxide and methane emissions.[53]
- **Contamination:** The build-up of microplastics and microfibres from poor plastic waste management and sewage sludge applications is a growing concern for agricultural soils.[54,55] For example, the unknown prevalence of microplastics from sewage sludge application to fields creates difficulties in assessing the potential ecosystem and human health consequences.[56] Recent research has shown some impacts from exposure of earthworms to microfibres including lower weights, and decreased casting activity, which may impact soil function.[57,56]

Restoring the soil system
Various soil stewardship approaches have promoted principles such as organic farming,[58] regenerative agriculture[59] and conservation agriculture[60] to restore soil functions. Organisations like the Soil Association have produced reports on how best to restore agricultural soils.[61,62] Organic farming involves management without the use of agrochemicals, such as fertilisers and pesticides. Regenerative and conservation agriculture focus more on returning organic material to the soil, keeping soil covered to reduce erosion and minimising, disturbance of soil to promote build-up of SOM.[74] However,

Box 2: Case Study – Biochar Demonstrator
There is an increasing research and policy interest in Greenhouse Gas Removal (GGR) strategies for carbon sequestration and storage (PN 618).[63] One potential technology is biochar, the burning of biomass at high temperatures in an oxygen-deprived environment to produce a black, charcoal-like product.[64,65] Biochar can be ploughed in or applied to the soil surface, although evidence for best practice is uncertain. The evidence base for biochar efficacy is more robust in tropical climates with clear improvements to yield (PN 358)[66], but the effects in the UK are less certain. Some evidence suggests co-benefits of biochar include reduced methane[67] and nitrous oxide emissions,[68] but the applicability of this to the diversity of UK soils is unknown. Although the research evidence is mixed, the emissions footprint of biochar production and application is typically less than the carbon offsetting benefits.[69,70]

The UKRI Biochar Demonstrator[71] aims to address uncertainties around biochar use in a UK context. Trials have been established in the Midlands and Wales on agricultural sites to investigate the effects of biochar additions. For example, trials are underway to compare the effects of applying biochar produced from biomass residues and virgin wood in different agricultural systems and soil types. Another objective is to identify the quantity of biochar that can be applied to maximise carbon sequestration and storage effects, and improvements to soil fertility.[72] Measures such as biochar application could be funded through private markets and a soil carbon code has been proposed.[73]

there are many uncertainties around the restoration of soils, not least due to a lack of ongoing monitoring data on condition.

Restoring natural features
Measures to restore natural vegetation communities and processes may be needed as part of an ecosystems approach to restoring soil functions and services (PB 42) at landscape scales. These could include hedgerow planting, natural grassland communities and rewilding (PN 537),[75,76] but these may decrease the area available for food production.

Fertilisers and soil additions
Synthetic fertilisers, such as ammonium nitrate, are manufactured, as opposed to organic fertilisers, including livestock slurries, manures and compost, or sewage sludge. Manufacture of synthetic nitrogen fertilisers result in CO_2 emissions from fossil fuel use (41 to 51% of the GHG footprint of wheat and barley production[77]). Excessive use of fertilisers, particularly on compacted or waterlogged soils, causes significant nitrous oxide emissions.[78,79] Some soil bacteria convert synthetic nitrogen into nitrate before the plant can take up the nutrient, whilst others convert nitrate back to nitrogen, also producing nitrous oxide.[80] Organic additions increase carbon inputs and other nutrients in the soil from the residue biomass,[81] although slurries in particular can still result in N_2O emissions if applied at the wrong time of year to waterlogged soils.[82] Nitrates and phosphates from fertilisers can also leach into waterways when soil is eroded, affecting water quality. To address excessive use, precision techniques are increasingly used for the application of fertilisers (PN 505).[83] The carbon benefits of soil additions such as biochar are also being researched (Box 2). This could add more carbon to the soil for storage over a long time period.

Tillage
Conventional tillage involves ploughing the topsoil for aeration, weed control and creating a seedbed for cultivation. Conservation-tillage options include minimum (reduced) tillage, which involves no deep ploughing but some disturbance in the top few centimetres of soil, plus incorporation of organic additions. Another option is no (zero) tillage, which involves the direct drilling of seed into the residues of previous crop and cover.[84] There is clear evidence that SOM and SOC are reduced under more intensive tillage, affecting soil biology.[84–86] The effectiveness of minimum or no-till compared to conventional practices is debated. Results are mixed in the UK context due to the cool, moist climate and range of soil types being unsuitable for no-till in some areas. Some evidence suggests farmers are switching to no-till in the UK[87], although this may be limited to clay soils, and may result in reduced yield for at least 3 years and increased use of herbicides to control weeds.[88,89]

Cover cropping and leys
Cover crops are planted to keep soil covered before a main crop is sown. Cover cropping has numerous benefits, including improving soil functions.[90] For example, when plant mixes are used, more diverse rooting systems are present, leading to improved soil structure, nutrient cycling, improved carbon storage and biodiversity.[91,92] Introducing legumes (such as beans or pulses) reduces the requirement for synthetic nitrogen additions as symbiotic bacteria fix nitrogen directly from the atmosphere.[93] Additionally, many cover crops can be grazed by livestock or ploughed into the soil and the organic residues feed the soil biota.[58,94,95]

Another option for arable land managers is to include grass leys, a season of growing grass instead of a crop, into the rotation to keep soil covered. Co-benefits of leys include increased SOC as grasses are less disturbed by machinery and chemicals, and storing carbon for longer than annual crops.[96] Similar to cover crop mixes, leys planted with multiple grassland species, such as clovers and lupins, are beneficial for soil structure through root diversity and nutrient cycling, as well as for biodiversity.[97] Introducing grazing livestock into arable rotations to graze leftover stubbles, cover crops and grass leys is also an increasingly popular option in England.[98,99] The key benefits of rotating livestock are that organic manures left on the soil increase carbon inputs and replenish nitrogen reducing the use of synthetic fertilisers.[28]

Soil policy and monitoring
The past decade has seen a growing policy interest in soils as the impacts of soil degradation on carbon stocks and wider ecosystem services has come under scrutiny.[100] Box 3 outlines the timeline of soil-related policy initiatives in the UK since 2009. Key ambitions include: a UK Government pledge to ensure soils are sustainably managed by 2030,[101] which was reiterated in the 25 Year Environment Plan;[102] to increase monitoring and restoration of soils, as described in the Soil Health Action Plan for England (SHAPE).[103] The Sustainable Farming Incentive (SFI) will pay farmers to protect and restore soil health through SOM testing and soil assessments.[104] Soil stewardship will be incentivised under the 'arable and horticultural soils standard' and 'improved grassland soils

Box 3: Soil policy initiatives
Policy efforts around soil health protection and restoration have been made in previous years:

- The UK Government's *Safeguarding our Soils* (2009), *Protecting our Water, Soil and Air* (2009) and *The Natural Choice: securing the value of nature* (2011): soils valued for wider ecosystem benefits and a goal set for England's soils to be managed sustainably by 2030, and degradation threats tackled successfully.[101,105,106]
- The Environmental Audit Committee (2016) published a report into Soil Health and the feasibility of achieving the sustainable soils by 2030 target.[107]
- The 25 Year Environment Plan (2018) reiterated previous targets of soil management but highlighted improved monitoring at national and farm-scale, including £200,000 to develop appropriate soil health metrics.[102]
- Agriculture Act 2020: incentives mentioned for farmers to protect and improve soil health. Environmental Land Management (ELM) schemes, including the Sustainable Farming Incentive (SFI), will be brought in from 2024 to replace the Common Agricultural Policy.[108]
- Environment Act 2021: No soil health framework or targets set. The new strategy, the Soil Health Action Plan for England (SHAPE), has recently been announced to restore soil health linking, and the SFI incentives.[109]

Box 4: Soil Essential Biodiversity Variables (EBVs)
Biological components of soils can vary extensively depending on soil function, land use and management.[115] Soils constitute a variety of organisms (PN 601):[97,116–118]

- Microorganisms (bacteria & fungi) decompose organic matter.
- Microfauna (protozoa & nematodes) consume the microbes.
- Mesofauna (mites & springtails) decompose surface litter.
- Macrofauna (earthworms, termites & large organisms) alter the soil structure.
- Essential Biodiversity Variables (EBVs) are measurements required to monitor biodiversity changes and can be applied to soil organisms and functions using soil-specific indicators.[112] Using this framework, soil health can be assessed alongside soil biodiversity, which heavily influences soil chemical and physical properties. Evidence suggests that soil EBVs could be a useful indicator framework and are timely given current policy efforts, such as SHAPE (Box 3).

standard'. Introductory levels are expected to pay farmers £22/ha and £28/ha, and intermediate levels at £40/ha and £58/ha, respectively for the two soil standards.[110] However, paying farmers for outcomes rather than practices has been criticised by researchers.[100,104] If the outcomes of measures are to be evaluated, trends in soil condition need to be assessed against relevant baselines or benchmarks. Indicators are needed that provide a measure of the physical, chemical, biological, and functional state of the soil, as well as robust measuring, reporting and verification (MRV) methodology.[7,111] Soil also forms slowly and evidence suggests SOC could take over 10 years to reach a new equilibrium, although soil biology may respond faster. The long-time frames for soil processes creates issues around benchmarking and monitoring timelines.

Soil indicators
There are over 700 soil types in England,[16,101] which makes identifying measures relevant to different types that represent soil health difficult. Recent research suggests that measures of soil Essential Biodiversity Variables (EBVs, Box 4) can be linked with soil ecological indicators to assess the status of soil health.[112] Another key indicator of soil health mentioned frequently in the literature is the content of organic carbon. The '4 per 1000' initiative is encouraging governments to increase SOC stock by 0.4% per year in topsoil to mitigate atmospheric CO_2 concentrations, giving soils a critical role in climate mitigation.[113] However, this has been criticised for the lack of consideration of system variation, such as grasslands that may already be close to the limit of carbon that can be stored in soil, and permanence of SOC in soils, i.e., due to land management.[114] Like soil biology, SOC is also highly connected to other soil variables with research indicating a SOC to clay content ratio could be a simple, single measure of soil health.[5]

Monitoring, reporting and verification (MRV)
National scale MRV of soils is limited in England, with the last audit being the 2007 Countryside Survey (CS2007).[119] This means that there are large gaps in recent data about the state of soils, putting increased reliance on individual site-specific measurements from the peer-reviewed literature, and modelling efforts using available data and current information about land use.[120] Funding from the Natural Environment Research Council allowed the CS to restart in 2019, measuring soil and vegetation responses to land use and climate change every 5 years.[121] Consensus amongst the academic community is that newer modelling and remote sensing techniques should be used to supplement robust, direct soil sampling measurements. Improving the selection of soil ecological indicators and policy support (such as SHAPE) may improve national MRV efforts.

Addressing uncertainties in risks for soils
Future risks to soil health are uncertain, particularly under the threat of climate change, where warmer, wetter winters and hotter, drier summers are to be expected in England.[122] Some researchers also suggest that improved soil biodiversity could buffer future shocks and increase overall soil resilience.[31,32,93,112] Recent advancements in technology and soil science may allow soils to be managed to increase resilience.

- **Volatile Organic Compounds (VOCs):** Electronic nose (e-Nose) technology can detect biological signals in soil and responses to management.[123]
- **Robotics and remote sensing:** Robots and drones are helping farmers make management decisions and precisely apply agrochemicals without damaging soil health.[124]
- **Soil spectroscopy:** A portable tool for use on-farm for quicker measurements of SOC. It also has the potential to measure a wider suite of characteristics.[125]
- **Circular economy of soils:** Agricultural by-products, such as manure and straw, can be recycled as fertiliser, bedding and feed.[126] Re-purposing of waste soils (such as construction soil) for agricultural use is done by treating them with appropriate nutrients and biological additions.[127]
- **Plant, soil and microbiome interactions (PN 601):** For example, recent research into breeding of ancient wheat varieties that suppress soil nitrification levels and reduce N_2O emissions may increase fertiliser use efficiency and mitigate climate impacts.[128]

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