OEP

Review of Evidence: Sustainable Management of Soils in England

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EXECUTIVE SUMMARY

Improving soil management is a key action under Goal 6 (Using Resources from Nature Sustainably) of the revised Environmental Improvement Plan for England. Defra has committed to support farmers to bring 40% of agricultural soils in England under sustainable management by 2028, increasing to 60% by 2030. In the light of this commitment, this project critically appraised (using Quick Scoping Review and SWOT analysis methodologies) the current regulatory and governance frameworks, and government and non-government schemes supporting the sustainable management of agricultural soils in England. The key findings were:

- There is no universally accepted definition of Sustainable Soil Management (SSM), and a lack of consensus over the metrics to be used for measuring changes in soil quality makes it difficult to determine whether SSM has been achieved in any given location.
- Over 50 individual soil and land management measures were identified that could contribute to SSM. These were organized into 6 categories: i) soil inputs; ii) grass & grazing management; iii) crops & rotations; iv) mechanical pressures & cultivations; v) measures relating to the physical environment; and vi) soil testing and monitoring, education and advice.
- There was considerable variation in the strength of the evidence base for these measures, with a large body of evidence supporting the benefits of organic material inputs and substantial research into no and reduce tillage methodologies (although the latter showed inconsistent effects on soil quality). Other potential SSM measures have been less well researched or lack evidence in an English context (e.g. measures relating to grass and grazing management), whilst some are still at the speculative stage or have not been proven to be effective for soils in England.
- Climate change will have important implications for SSM and the measures which can and should be adopted. Under future climate change scenarios, soil inputs and other SSM measures that build or maintain SOM levels will become increasingly important.
- The majority of existing legislation that directly links to SSM, focuses on controlling soil inputs to agricultural soils via non-farm organic materials or manufactured fertilisers, with a specific goal of reducing the risk of soil contamination (e.g. the Sludge (Use in Agriculture) Regulations 1989). There is little focus on other aspects of soil protection such as reducing the threat of soil loss, compaction or erosion. Other legislation (e.g. the Nitrate Pollution Prevention Regulations 2015 and Farming Rules for Water 2018) make reference to a number of SSM measures, but their primary focus is on protecting watercourses - any benefits to soils is seen as secondary to water quality improvements.
- Voluntary, government-funded schemes such as the Sustainable Farm Incentive (SFI) and Countryside Stewardship (CS) provide incentives for farmers to adopt sustainable farming practices, with some SFI actions supporting farmers to assess and improve soil quality. However, the driving force behind many of the measures within these schemes is on improving biodiversity and providing wider environmental benefits, with any benefits to soils appearing to be more of a secondary benefit or ‘side-effect’.
- Three best practice case studies were selected to demonstrate how regulatory and governance frameworks can support SSM in England. All recognized the need to maintain and improve soil quality/health and minimise environmental impacts. However, the over-riding and primary driver for all decisions on farm was financial, with SFI and CS payments seen as essential (although potentially inadequate) to support SSM.

- The SWOT analysis identified a number of reasons why it is potentially difficult to legislate for SSM. Appropriate management practices will vary depending on the function that the soil is required to fulfill, the farming system, soil type, topography, drainage, season and other factors outside a land manager's immediate control (e.g. supply chain demands). It is extremely difficult to police legislation where there is no clear definition of what is required and where SSM measures are so dependent on local conditions.

In the light of these findings, the adoption of many SSM practices is likely to be more effectively encouraged by voluntary, incentivised schemes rather than legislated for at a national level, with farmers able to select those practices that are more appropriate to their locality and farming system, supported and encouraged by improved training and advice, including facilitated peer-to-peer learning. There is a need to increase awareness of the value of soil and its many functions, with the focus moving away from improving single soil functions or addressing a specific soil threat, or meeting individual regulatory, grant or voluntary scheme requirements, towards a societal and financial recognition of the importance of soil ecosystem services (the public and private goods provided by healthy soils).

1 BACKGROUND AND OBJECTIVES

1.1 The importance of soil management

Soil is the foundation of all terrestrial ecosystems and provides multiple ecosystem service benefits; the most prominent of these being the provision of food and fibre, the maintenance of public health, climate regulation and carbon storage, the regulation of water flow and quality and the support of both above and below ground biodiversity. Different soils deliver some ecosystem services more effectively than others. For example, lowland mineral soils under arable and grassland management are important for food production, while deep peats in upland areas support semi-natural habitats and are arguably more important for carbon storage and climate regulation. However, the ability of soils to deliver these services is threatened by degradation processes such as erosion, compaction, loss of organic matter (OM), contamination and acidification.

The management of agricultural soils has a profound impact on soil quality and consequently the ecosystem services that soils provide. In particular, cultivations and crop rotations in arable production systems have led to reductions in soil organic matter (SOM) which has impacted on other soil properties including structural stability, water holding capacity and water infiltration rates. Estimates suggest that arable farming practices have led to a reduction in SOM levels of between 40% and 60% over recent decades (EA, 2019).

Compaction of soils due to machinery trafficking or livestock trampling, particularly when soils are wet, can cause a significant deterioration in soil structure, reducing the number and connectivity of soil pores and increasing bulk density. This has a direct impact on a number of key soil physical and biological processes, notably water infiltration, gaseous exchange, root access and soil faunal activity, with implications for crop productivity, water quality, flood management and biodiversity. Increases in runoff and erosion from compacted fields result in higher nutrient and sediment loads in water courses, while reduced infiltration rates increase the risk of flooding. Sub-optimal crop growth can lead to limited uptake of applied nutrients which increases the risk of nitrous oxide emissions to air and nitrate, phosphorus (P) and sediment losses to water. Leaving land bare overwinter or with little crop cover also increases the risk of soil damage and soil erosion.

Intensive agriculture has disrupted the soil nutrient cycle across England with nutrient surpluses in livestock regions whereas arable regions rely on the use of imported nutrients to maintain soil fertility. For example, estimates suggest that the northwest of England, which has a high concentration of livestock farms, has an annual surplus of 2,900 tonnes of P, compared with the southeast of England which has a deficit of 14,400 tonnes of P per annum (Bateman *et al.*, 2011). Nutrient management planning is key to ensure that optimal and not excessive nutrient applications are made to support crop production and limit nutrient losses to the environment, whilst maintaining an appropriate soil pH is important to control the availability of crop nutrients.

Soil contamination can have severe impacts on food production, soil biodiversity and functions reliant on microbes. In addition to contamination from industrial activities there is a risk that land applications of organic materials from industrial and urban sources (e.g. anaerobic digestate, composts and biosolids) can be a source of physical (e.g. plastics, glass etc) and chemical contaminants (e.g. potentially toxic elements - PTEs, persistent organic pollutants).

The majority of soil ecosystem services are driven by biological processes, underpinned by SOM decomposition. Organic matter provides a food source and habitat for the soil biological community, drives the cycling of nutrients within soils and is a central component of soil aggregation and the maintenance of structure and water relations. Management practices that improve soil quality over the long term typically involve ways to maintain or increase SOM content. These include introducing grass into arable rotations, planting cover crops in spring cropping systems, incorporating crop residues into the soil, using organic materials and implementing reduced or no-till cultivation systems.

Healthy soils require a balance of biological, chemical and physical properties to ensure good soil function. National soil monitoring schemes provide valuable data on the state of UK soils. However, it is also important to provide simple, easy to interpret indicators of soil quality to enable farmers and land managers to understand the quality of their soils at a local level and monitor changes over time in response to management measures. The five-year (2017-2022) ADHB/BBRO Soil Biology and Soil Health partnership (https://ahdb.org.uk/soil-biology-and-soil-health-partnership) aimed to address this and identified benchmark values for the following key soil parameters considered necessary to quantify a 'healthy soil' *viz*,: SOM, pH, extractable P, K, and Mg, Visual Evaluation of Soil Structure (VESS) and earthworm numbers. More recently, a JNCC report (Harris *et al*., 2023) set out a new approach to soil health for England to account for the need to assess the health of soil from both the national and individual land manager perspectives, and in relation to the range of ecosystem services that soils provide. Under this approach (Figure 1), the links between soil properties and ecosystem services are regularly reviewed to create ecological models for each ecosystem service. Different soil metrics and other parameters (e.g. climate variables), are identified and incorporated into statistical models populated with relevant national datasets. The outputs give an indication of soil health in relation to a particular ecosystem service for any selected land parcel, and allow comparison with typical values for soils with similar properties across all land uses; users can also explore how different management options could impact soil health across a range of ecosystem services.

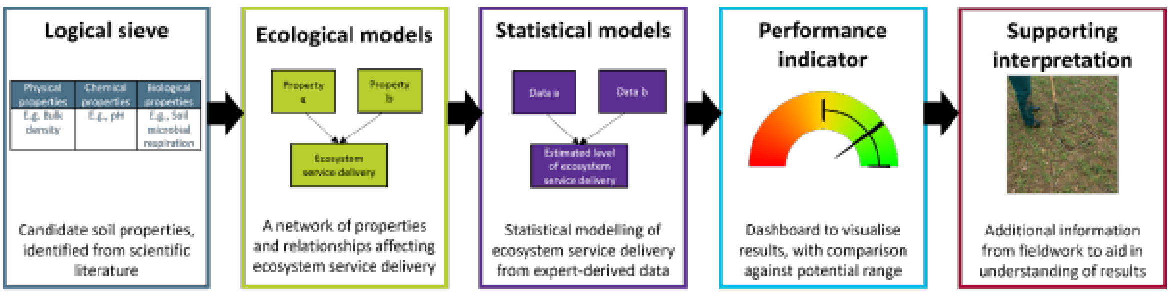

Figure 1. General approach for soil health assessment (from Harris *et al*., 2023).

1.2 Overview of regulations and incentives to support sustainable soil management

Improving soil management is a key action under Goal 6 (Using Resources from Nature Sustainably) of the revised Environmental Improvement Plan (EIP) for England. Defra has committed to support farmers to bring 40% of agricultural soils in England under sustainable management by 2028 and increase this to 60% by 2030 (Defra, 2023).

1.2.1 Regulations

Up until December 2023, farmers receiving payments from the Basic Payment Scheme had to comply with the requirements of Cross Compliance and maintain their soils in Good Agricultural and Environmental Conditions (GAEC). In order to comply farmers had to provide minimum soil cover (GAEC 4), minimise soil erosion (GAEC 5) and maintain the level of OM in soil (GAEC 6). Cross compliance has been replaced with a series of rules, which include managing land to prevent soil erosion and planning inputs, underpinned by the Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018 (Farming Rules for Water – FRfW; SI, 2018)[1] . The FRfW were introduced in 2018 across the whole of England and require farmers to carry out nutrient management planning to ensure that nutrient applications from all sources meet and do not exceed soil and crop need. The FRfW also require farmers to sample and analyse every 5 years., although soil SOM analysis is not required.

Other regulations governing the management of soils in England focus on controlling the risk of soil contamination with PTEs and managing soil nutrients. The Sludge (Use in Agriculture) Regulations (SI; 1989) were first introduced in 1989 and form the basis for the Code of Practice for the Agricultural Use of Sewage Sludge (DoE, 1996), which restrict applications of biosolids to ensure that PTE concentrations in soils do not reach toxic levels. The requirements of the Code of Practice (DoE, 1996) have been included in the water industry supported Biosolids Assurance Scheme which sets the standard for biosolids recycling in England. Other Codes of Practice that support the safe recycling of organic materials to land include the Compost and Digestate in Agriculture: Good Practice Guide. The Nitrate Pollution Prevention Regulations (SI, 2015; SI, 2016) places limits on the amounts of organic materials that can be applied to land and on the timing of high readily available N manure and manufactured fertiliser N application in Nitrate Vulnerable Zones (NVZs) which cover around 60% of agricultural land in England.

1.2.2 Government incentives and voluntary schemes

Recent government incentives to improve the management of soils include the introduction of the Arable and Horticultural Soils Standard and Improved Grassland Soils Standard under the Sustainable Farming Incentive (SFI) in 2022 and subsequent "actions for soils" under the SFI 2023 offer. Under the scheme farmers are rewarded for actions that protect the soil from erosion and increase SOM. Farmers are supported to carry out baseline soil health assessments and develop strategies to manage their soils sustainably. In contrast to the FRfW, SOM analysis is required under the "SAM1" SFI action: "Assess soil, produce a soil management plan and test organic matter". Voluntary initiatives such as the LEAF Soil Management and Fertility Standard and Red Tractor also require soil and nutrient management planning for compliance. Some water companies have payment for ecosystem services (PES) schemes offering farmers payment for taking various actions in their catchments (e.g. growing cover crops), although these are mainly aimed at improving water quality rather than focussing on soil management (see Roberts *et al*., 2021).

Government incentives and voluntary schemes are discussed in more detail later in Sections 5 and 6.

[1] This legislation is henceforth referred to in this report as the Farming Rules for Water (FRfW)

1.2.3 Guidance

There is a large amount of guidance and incentives available to manage soils effectively. The MAFF Code of Agricultural Practice for the Protection of Soil published in 1998 set the standard for practices to maintain soil fertility, minimising compaction and controlling soil erosion. This information has been supplemented by publications such as the EA 'Think Soils' manual published in 2007, and AHDB's 'Healthy Grassland Soils' booklet published in 2015 and 'Principles of Soil Management' booklet published in 2019. Other sources of advice include the Championing the Farmed Environment (CFE) booklets on 'Managing Soils for a Sustainable Future', information published on various Defra, AHDB and other organisations' webpages (see Section 2.2, Section 5 and Section 6), and the British Society of Soil Science (BSSS) 'Guidance and science notes' webpages.

It is important that guidelines to inform sustainable soil management should account for the different soil types, agro-climatic zones and land use that the soil is supporting. In addition, soil analysis and testing to derive soil quality indicators should be appropriate for combinations of soil types, land use and climatic conditions.

1.3 Project objectives

The overall objective of this project was to provide a critical appraisal of the current regulatory and governance frameworks, and government and non-government schemes supporting the sustainable management of agricultural soils in England.

The detailed study objectives were to critically appraise the following:

(i) Sustainable management of soils under different land use scenarios.

(ii) Current regulatory and government schemes implemented in England that impact directly or indirectly on the sustainable management of soil.

(iii) Current non-governmental schemes implemented in England aimed directly or indirectly at the sustainable management of soil and their contribution in principle and in practice to protecting soil in England.

(iv) Best practice case studies which can be used as exemplars of regulation and governance supporting the sustainable management of soil.

(v) Strengths and weaknesses in government's regulatory/governance framework for the sustainable management of soils.

2 METHODOLOGY

2.1. Review of the literature on sustainable soil management (SSM) definitions, principles and practices

An initial review of the literature was undertaken to:

i) Understand and define the meaning of the term 'sustainable soil management (SSM)'.

ii) Identify a set of sustainable soil management measures appropriate for agricultural soils in England under different land use scenarios (arable, grassland and horticulture).

iii) Assess the evidence base underpinning the effectiveness of each measure for achieving sustainable soil management goals.

iv) Assess the impact that changing climatic conditions might have on the importance and effectiveness of the different measures.

The literature was interrogated using keyword searches of Google Scholar (for the years 2015-2023) to identify peer reviewed scientific publications and Google to identify any 'grey' literature (e.g. reports, responses to consultations). In addition, searches were made of the Defra Data Science and Research Projects database, and the BBSRC and the AHDB research projects and reports databases to identify any relevant past and present UK-funded research projects. See Appendix 1 for more details of the searches undertaken.

The literature located in the searches was supplemented, where appropriate, with key references identified by members of the project team who have many years of agricultural soils research expertise and practical experience of working with farmers, land managers and policy makers.

2.2. Mapping of measures across regulations, and government and non-government voluntary schemes

The SSM measures identified in the literature were 'mapped' across to the current regulations and selected voluntary schemes operating in England. A list of regulations and voluntary schemes was developed in consultation with ADAS soil scientists, relevant stakeholders (as identified in consultation with the OEP project team) and the OEP project team, and comprised those which could potentially be relevant for SSM as a concept or could impact the implementation of specific SSM measures. The mapping process was used to target the literature searches on the efficacy of the regulations on voluntary schemes (described in Section 2.3), and to identify any strengths and weaknesses in the regulatory framework in England.

2.3. Review of the literature on regulations and voluntary schemes related to sustainable soil management

A quick scoping review (QSR) is a systematic and transparent process to identify, critically appraise, and synthesise evidence which aims to reduce the potential for bias. The purpose of this QSR was to review and synthesise current thinking, research and evidence on the effectiveness of the current regulations and government/non-government voluntary schemes relating to the sustainable management of soils in England. The specific research questions addressed by the QSR were:

Q1. How does the current regulatory framework and government schemes in England relate to the sustainable management of soils?

Q2. How do current non-government schemes in England relate to the sustainable management of soils?

The output from the mapping of measures (Section 2.2) was used to guide the QSR with the evidence identified in the literature used to inform the subsequent Political, Economic, Sociological, Technological, Legal and Environmental (PESTLE) analysis. The PESTLE framework provided a clear structure for the presentation of the peer reviewed literature and expert opinion on the political, legal, and social dimensions of the SSM measures. It was not possible to explore the economic aspects of the SSM measures in depth, however these are briefly referred to in the context of the SWOT analysis (see Section 7). The environmental and technological implications of the SSM measures are explored in Section 5 of the report, and also referred to in the SWOT analysis. The detailed methodology for the QSR and PESTLE analysis can be found in Appendix 2 and 3.

2.4. Best practice case studies.

Following liaison with farmers and stakeholders, 3 best practice case studies were selected to demonstrate how regulatory and governance frameworks can support SSM in England. The selected farms covered a range of geographical areas, cropping systems and soil types. An online interview was conducted with each case study farmer to discuss:

- Soil quality issues on farm
- Soil management practices
- Nutrient management
- Soil monitoring
- Motivations and incentives

A transcript of each interview was produced and a summary was sent to each participant for them to confirm the accuracy of the reported interview outcomes.

2.5. Identifying strengths and weaknesses in the regulatory framework for the sustainable management of soils.

The purpose of a SWOT analysis is to identify success factors (Strengths), areas for improvements (Weaknesses), areas for increased impact and success (Opportunities), and external factors that could or should be mitigated (Threats). In the context of this study, this involved understanding where existing regulations and/or government and non-government voluntary schemes were currently operating, where gaps exist, and identifying how these could be addressed to mitigate current and future threats to SSM. The SWOT analysis was undertaken through an internal meeting of the project team including three ADAS senior soil scientists with many years of experience and expertise relating to the implementation and outcomes (positive and negative) of the SSM measures being considered. This expert insight was supported through the evidence identified from the literature and summarised in Section 5, and with the results of the QSR and PESTLE analysis.

The analysis was conducted for each broad category of SSM measure, rather than for individual measures as there was a large degree of commonality across measures in a category. The SWOT analysis was approached from an economic, environmental, scientific, social, general perspective defined as follows:

- **Economic**: costs of implementation and/or savings that could be generated by this measure. Given the scope of this work, economic assessments were based on qualitative expert insight.
- **Environmental**: assessment of whether current regulations address any negative environmental impacts that arise from the implementation of measures. Additional evidence on environmental impact beyond agricultural production was also captured.
- **Scientific:** weight of scientific evidence (i.e. size and quality of the peer reviewed evidence base associated with the measure/category)
- **Social** – evidence for the extent of the implementation of measures (i.e. are farmers presently carrying out the measures in this category? If not, is it due to a lack of knowledge or lack of capacity?)
- **General** - expert opinion which does not fit into the other themes but should be considered.

The outcome of the SWOT analysis is summarised in tabular form in Section 7 and the findings were used to inform the recommendations in Section 8.

3 DEFINING SUSTAINABLE SOIL MANAGEMENT

3.1. Definitions

In their paper discussing soil security, McBratney *et al.* (2014) proposed that the key to sustainable soil use was to match its intended use to its capability i.e. "*soil should not only be viewed through a lens focusing on its ability to produce*". The 'Evidence Review on Soil Research' prepared for Defra and published in 2015 set out to describe the UK research evidence on SSM for delivery of three key ecosystem services, namely food production, water and nutrient cycling and climate change mitigation (Smith *et al.*, 2015). In this report, soil sustainability was defined as "*the continued ability of a soil to provide essential ecosystem services and soil functions, as well as its resilience to change. A sustainable soil is therefore one that is able to perform the key functions that society requires from it, both now and in the future, is resistant (does not change to a significant degree) and resilient (recovers to its former state) to disturbance and perturbation*". However, the report goes on to say that some degree of change may have to be expected in the long term (many decades) if there are changes to soil and air temperatures and soil wetness regimes as a results of climate change.

Since then, various review papers have identified many definitions of SSM proposed by different authors from around the world. In their global systematic literature review on SSM practices[2], Sharna *et al.* (2023) quoted some definitions from the 1990s:

- Soil management is the "*manipulation of soil involving a diverse range of practices for its use, restoration and conservation"* (Robinson, *et al*, 1994).
- Sustainable Soil Management is "*the use of technologies and options which are economically viable and socially acceptable, aimed at simultaneously maintaining/enhancing productivity, reducing production risk, protecting the potential of natural resources and preventing degradation of soil and water quality* (Smyth *et al*., 1993).

More recent examples from the literature were cited by Jayaraman *et al* (2023):

- "*Soil management that meets the needs of the present without compromising the ability of the future generations to meet their own needs from that soil*". (Smith & Powlson, 2007).
- Soil health is the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems. It follows that "*in managed systems, soil health can be maintained, promoted or recovered through the implementation of sustainable soil management practices*" (FAO/ITPS 2020).

A recent study of SSM in the UK (Jaworski *et al*., 2024) begins by stating that SSM "*refers to land management practices that not only help to prevent soil erosion but also help to enhance the multi-functionality of the soil, which is often conceptualized as soil health*". They also explain that there is no single definition of SSM, as different practices are required in different soil and agro-ecological contexts, however it should encompass practices that can simultaneously improve soil biology, soil structure and nutrient status and reduce reliance on expensive chemical inputs. They argue that achieving SSM depends on the adaptation and adoption by land managers of a set of combined

[2] Note that in this report the terms practice and measure are used interchangeably to refer to an action that could be adopted by a farmer, land manager or policy maker to contribute towards or promote SSM.

practices contributing to minimal soil disturbance, crop diversification and maintenance of living and/or non-living soil cover.

It could also be argued that SSM is the implementation of those practices which are crucial for achieving the United Nations (UN) Sustainable Development Goals (see, for example, Hou *et al*., 2020; Figure 2) and that SSM is essential for attaining food and nutritional security, and ecosystem services (Jayaraman *et al.*, 2023); Figure 3). Interestingly, the very recent House of Commons Environment Food and Rural Affairs Committee report on Soil Health (HC, 2023) does not attempt to define SSM, but uses *"the term 'sustainable' broadly in reference to those practices thought to be more environmentally friendly in specific contexts*". The report does, however, call for a clear and agreed definition(s) of SSM which "*will have to be a flexible, reasonable but stretching definition, agreed with other important stakeholders*."

Figure 2. The relevance of soil to the UN Sustainable Development Goals (Hou *et al*, 2020). Note: SDG15 is exclusively for life on land, not all life on earth (as implied here), which includes Life below water (SDG 14).

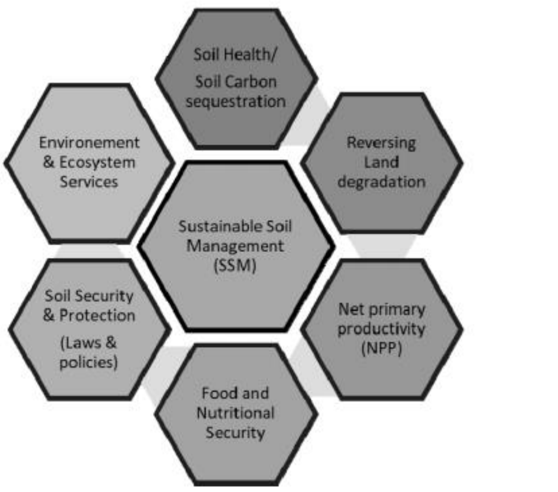

Figure 3. The close relationships between SSM and soil functions and ecosystem services (Jayaraman *et al*., 2023

In terms of an internationally recognised definition, probably the most widely accepted is that published by the UN Food and Agriculture Organisation (FAO) in their Voluntary Guidelines for Sustainable Soil Management (VGSSM) whereby *"Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity."* (FAO, 2017). By contrast, the EU Soil Strategy for 2030 (EC, 2021), states that "*there is no agreed common definition at EU level of SSM… that is concrete and complete to be enforceable*", and describes it more generally as " *a set of practices that is able to maintain the soil in, or restore it to, a healthy condition yielding multiple benefits, including for water and air*".

New work continues to be published on SSM, including a recent paper from the EJP SOIL project SERENA, which looked at the terminology used across the EU in relation to SSM and asked whether we speak one language on this issue (Weninger *et al*., 2024).

3.2. Principles

In 2016, the UN published a short document which defined six principles for SSM namely Protect, Restore, Maintain, Enhance, Develop and Communicate (UN, 2016; Figure 4). It is interesting to note that the principles relating to extension services, knowledge and innovation (5) and to communication (6) seem to have been largely ignored in later studies on SSM. We return to this topic later in Section 5.6.3 of this report.

The six principles were developed and expanded by the FAO in 2017 in a set of voluntary guidelines (FAO, 2017) in which it is stated that SSM is associated with:

- Minimising soil erosion by water and wind;
- Enhancing SOM content (i.e. SOM is stable or increasing and ideally close to the optimal level for the local environment);
- Preventing and mitigating soil compaction (i.e. soil structure is not degraded and provides a stable physical context for movement of air, water, and heat, as well as root growth);
- Providing sufficient surface cover (e.g. from growing plants, plant residues, etc.) to protect the soil;
- Fostering the soil nutrient balance and cycle (availability and flows of nutrients are appropriate to maintain or improve soil fertility and productivity) and reduce losses to the environment;
- Preventing, minimising and mitigating soil acidification, salinization, sodification and alkalinization;
- Improving soil water management so that water (e.g. from precipitation and supplementary water sources such as irrigation) is efficiently infiltrated and stored to meet the requirements of plants and ensure the drainage of any excess;
- Preventing and minimising soil contamination (i.e. contaminants are below toxic levels which would cause harm to plants, animals, humans and the environment);
- Preserving and enhancing soil biodiversity to provide a full range of biological functions;
- Ensuring that soil management systems for producing food, feed, fuel, timber, and fibre rely on optimized and safe use of inputs; and
- Minimising soil sealing through responsible land use planning.

More information on the background and aims of the VGSSM and its implementation in Italy can be found in Altobelli *et al*. (2020).

1. PROTECT SOIL FROM PHYSICAL, CHEMICAL AND BIOLOGICAL DEGRADATION, LIMIT EROSION AND AVOID DEFORESTATION

Maintain our current soil quality. Prevent soil loss, erosion, toxicity and compaction and eliminate deforestation:

- Keep soil covered.
- Avoid the unnecessary disturbance of soils; encourage conservation agriculture, no-till, and the proper drainage of soils.
- Choose geographically and agro-ecologically appropriate cropping systems, and encourage crop rotation.
- Employ established practices that control erosion and invest in the development of new approaches to prevent erosion.
- Limit the likelihood of soil contamination from all sources.
- Eliminate deforestation and allow our forests to naturally sequester carbon, while investing in reforestation.
- Discourage the cultivation of physically marginal soils.
- Establish sustainable grazing patterns to prevent overgrazing and potential desertification, and build buffers to prevent the expansion of deserts.
- Reduce the urbanization of agricultural land.

2. RESTORE SOILS ON DEGRADED AND MARGINAL LANDS

Recover the stranded, idle, economic and environmental assets that are degraded and marginal lands:

- Conduct assessments of soil and land degradation.
- Understand to what level soils have degraded, examine the timeline involved and prepare appropriately for what it will take to bring the soil back to productivity.
- Rebuild soil structure, actively increase or maintain soil carbon and organic matter levels, and rebuild nutrient content and balance.
- Restore topsoil to historic depths.
- Encourage whole systems management at the global, national and local levels.

3. MAINTAIN SOIL-BASED ECOSYSTEM SERVICES, WATER AVAILABILITY AND QUALITY

Recognize and manage and sustain the ecosystem services and habitat that soil provides and contributes to:

- Manage soil and water in tandem.
- Use the appropriate balance of fertilizers at the right time of year, in the right amount while avoiding ecologically sensitive areas of the field.
- Encourage and protect beneficial microbial and biochemical activity in soil.
- Promote soil resilience as a gateway to climate resilient agriculture.
- Create buffers and riparian margins between agricultural land and water sources.
- Choose geographically appropriate and sustainable irrigation practices.
- Encourage 'crop stability assessments,' 'environmental impact assessments' and 'high conservation value assessments,' especially when considering land use change.

4. ENHANCE SOIL PRODUCTIVITY ACCORDING TO ITS NATURAL CAPACITY

Ensure global food security through 'sustainable intensification', narrowing the 'yield gap' and replacing the nutrients we remove from the soil:

- Sustainably intensify productive agricultural systems.
- Employ an integrated approach to soil fertility management and replenish nutrients removed by the crop harvest.
- Maximize the organic cycle, utilizing organic and mineral fertilization as appropriate and apply the right balance of crop nutrients – both macro and micro.
- Make the appropriate crop selection for climate and soil type.
- Maintain crop residue cover.
- Manage the integration of livestock as a nutrient management tool.
- Reduce soil salinity and correct soil pH appropriately.
- Encourage the use of pyrolitic stoves among smallholders and the use of biochar.

5. DEVELOP EXTENSION SERVICES, KNOWLEDGE SYSTEMS, AND PROMOTE INNOVATION

Rebuild our global agricultural extension system to meet the demands of the twenty first century:

- Encourage increased investment in private sector and public extension services.
- Ensure that women and young people are specifically targeted by extension services.
- Provide hands-on training for farmers and agri-dealers.
- Encourage investment in innovation and the development of responsible and ecologically sustainable new technologies including improved farming practices, fertilizers, crop protection systems, seed varietals and species.
- Test, classify and map soils. Integrate existing data and provide specific fertility and management recommendations by crop and soil type.
- Create knowledge sharing platforms to promote best practices, make soil data widely accessible and develop long-term soil monitoring systems.
- Encourage appropriate mechanization while avoiding soil compaction.

6. COMMUNICATE THE IMPORTANCE OF SOIL

For the general public, farmers, policy makers, business and civil society:

- Advertise the importance of soils, economically, socially and environmentally.
- Promote knowledge sharing and partnership between government, business, academia and civil society that sets a minimum standard for soil awareness, management and protection.
- Provide training and advice for policy makers so that they can make informed decisions.
- Establish an agricultural curriculum in schools and encourage young people to explore advanced education and a career in agriculture.
- Take the pressure off soil to produce so much food by educating the value chain from consumer to farmer on how to reduce food waste.

Figure 4. The Six principles for Sustainable Soil Management (UN, 2016)

Broad approaches towards achieving SSM are many and varied, and could include conservation agriculture[3], regenerative farming[4], organic farming[5], the 4 per thousand initiative, nutrient

[3] Conservation agriculture is "a sustainable and resource saving agriculture production system comprising a set of farming practices adapted to the requirements of the constituent annual and perennial crops and local conditions of each farm and region, whose farming and soil management techniques protect the land from erosion and degradation, improve its quality and biodiversity, and contribute to the preservation of the natural resources, water and air, while optimizing yields and total farm output". (CA-UK).

[4] Regenerative farming is defined as "a system of principles and practices that generates agricultural products, sequesters carbon, and enhances biodiversity at the farm scale" (Burgess *et al.*, 2019)

[5] Organic farming is a system of farming and food production which aims to produce high-quality food, using methods that benefit the whole food system, from people to planet, plant health to animal welfare (Soil Association).

management plans, agroforestry, integrated pest management, agroecological systems[6] etc. A national stakeholder consultation in the 24 EU countries participating in EJP SOIL (Keestra *et al.*, 2023) pointed out that 'climate smart' SSM needs to consider agricultural systems in their entirety (e.g. agroforestry, organic agriculture, conservation agriculture) rather than looking only at individual agricultural practices (e.g. no tillage, crop residue return).

Other European researchers refer to SSM in terms of 'suites of practices' that could potentially benefit soil quality (e.g. Rust *et al.*, 2020). Thorsoe *et al*. (2023) describe SSM as "*a set of practices that are able to maintain the soil in, or restore it to, a healthy condition yielding multiple benefits, including for water and air*". However, it is not straightforward to define SSM practices since various soil physical, biological and chemical processes must be accounted for, and soils and soil properties are diverse across different scales, together with different land-uses, pedo-climatic conditions, access to inputs, machinery, technology, multiple public policies and socio-cultural values. Hence soil management decisions often involve trade-offs between mutually exclusive outcomes such as mitigation of greenhouse gas (GHG) emissions, yield optimization and biodiversity protection. Moreover, pedo-climatic conditions vary across regions, and SSM solutions must be tailored to the conditions and the specific challenges they entail.

3.3. Pressures and drivers for SSM

As discussed above, SSM is a term that can be used to refer to land management practices that aim to prevent soil degradation, which in turn can be described as the loss of both soil quantity and soil quality. Gregory *et al.* (2015) identified eight degradation threats to soils in the UK, namely erosion, loss of SOM, contamination, compaction, sealing, brownfield development, salinisation, landslides and climate change. Similarly, in their recent paper on priorities for UK soils, Peake *et al*. (2022) identified the main soil degradation processes of concern across the UK as being compaction, erosion (mainly water erosion) and SOM loss. Other threats to soils included disruption to the soil nutrient cycle (leading to nutrient enrichment or depletion), soil contamination (local and diffuse), soil sealing (mainly in urban areas), land take, and the impact of climate change on carbon sequestration. In a recent POSTNOTE on 'Restoring Agricultural Soils' the pressures on UK soils were described in a similar way as being related to nutrient status, erosion, compaction and contamination (POST, 2022).

Alternatively, SSM can be seen as a way to preserve and enhance soil functions or ecosystem service provision, and the two are closely related. Strauss *et al*. (2023) concluded that the benefits for soil functions and reductions in soil threats were highly interlinked. They found that most of the proposed measures identified in their analysis of German stakeholder recommendations for SSM would influence multiple soil functions/threats simultaneously, and many of the soil functions/threats could be addressed by multiple SSM measures (Figure 5). Interestingly the soil threats identified in this paper also included 'biodiversity decline' but not 'nutrient enrichment/depletion'.

[6] Agroecology "is an integrated approach that simultaneously applies ecological and social concepts and principles to the design and management of food and agricultural systems" (FAO, 2018)

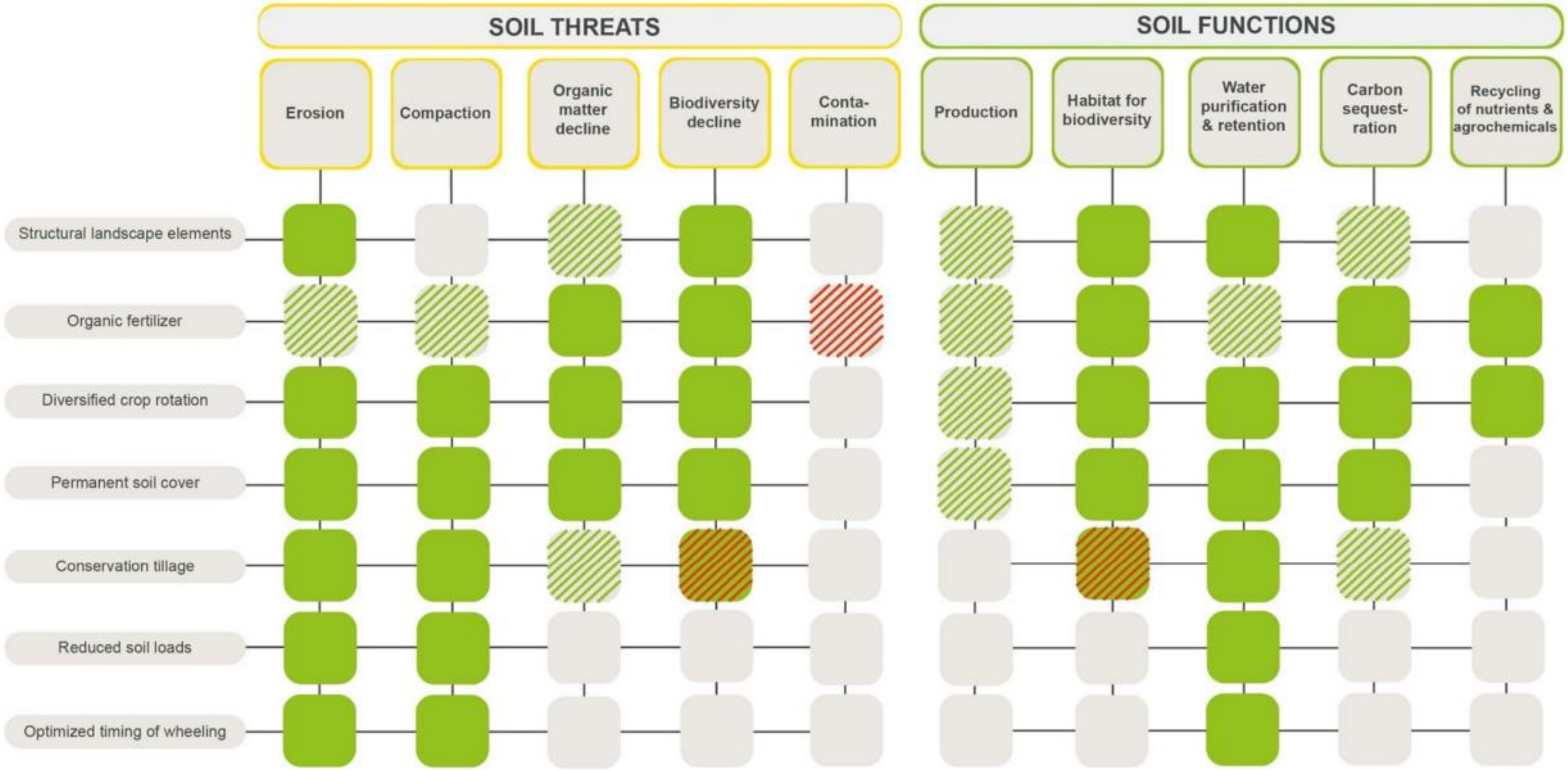

Figure 5. Linkages between the shortlisted SSM measures, and soil threats and functions. Green squares = positive linkage (i.e., mitigating soil threats/fostering soil functions). Grey squares = no linkages made. Striped squares: linkage weak or contested (green = positive, red = negative), Strauss *et al*. (2023).

The threats that face agricultural soils in the UK, as elsewhere, differ depending on land use, soil type and the agroclimatic conditions. For example, light arable soils and upland thin soils and deep peats are at greatest risk of erosion. The threat of soil loss via wind erosion on light and peaty soils can be addressed via specific management practices and policies, indicating that the perception of what constitutes a threat to soil is different depending on the local context. Another example might be that in livestock farming areas (e.g. parts of northwest England) there can be nutrient surpluses whilst arable farming areas in the southeast are highly reliant on imported nutrients (Peake *et al*., 2022), thus the threat of soil nutrient imbalances varies depending on the geographic area and the farming context. Grassland soils which are covered all year will be less at risk of erosion than horticultural or arable soils which (may) be left bare for part of the year.

3.4. Summary

There is no single agreed definition in the UK for SSM and no nationally recognised set of principles. The questions of what constitutes SSM, how this term is understood by UK farmers, how widely SSM techniques are used, and what the barriers and enablers are to adoption remain important knowledge gaps, which we aim to address to some extent in this project.

For the purpose of identifying practices which meet the goal of SSM, in this project it is defined as 'the adoption of soil management practices that promote soil health/quality and/or minimise the threats to soils, whilst maintaining agricultural productivity and minimising the risks to the wider environment'.

4 IDENTIFYING SSM MEASURES

In its guidelines on SSM, the FAO identifies farming practices that minimize soil pressures, such as cover crops, minimum tillage, crop rotation, optimised nutrient use and protection of carbon rich soils, but also presents practices that should be avoided, such as burning of vegetation and excess fertilisation. Similarly, Magistrali *et al*. (2022) explain that in the absence of a widely agreed definition of regenerative agriculture, they use the broad definition of Giller *et al*. (2021) which is not dissimilar to the FAO definition of SSM, namely "*farming systems and field operations that minimise soil disturbance, use diverse rotations and cover crops, and integrate grazing livestock, to reduce GHG emissions, build soil C, improve soil health and biology, enhance farm-scale nutrient use efficiency (NUE) and promote biodiversity and the ecosystem services that flow from it*."

Because of these similarities and overlaps, we have therefore used the literature relating to both SSM and regenerative agriculture to identify practical measures that could be used to contribute to the Defra goal of bringing 40% of agricultural soils in England under sustainable management by 2028 and 60% by 2030 (Defra, 2023).

4.1. SSM measures identified from non-UK literature sources

An interesting analysis of the published literature on the effects of various agricultural practices on soil quality was presented in a report on the impact of the CAP on SSM in Europe (EEIG Alliance Environnement, 2020). The analysis differentiated between activities which have:

Clear positive effects on soil quality: permanent soil cover (diversified crop rotation, intercropping, cover crops including catch crops and mulching including crop residues), application of organic amendments (compost, manure), permanently covered areas (e.g. forest, grasslands, wetlands), landscape elements (e.g. buffer strips).

Clear negative effects on soil quality: land-use changes from forest or grassland to arable land, intensive grazing, use of heavy machinery, chemical inputs, wetland drainage.

Different impacts on soil depending on the context: mineral fertiliser use, drainage, tillage (although for all of these effects on soil quality are complex and highly dependent on implementation method, soil conditions and the soil function and ecosystem services prioritised in each context).

Those practices with positive impacts on soil quality (in some or all circumstances) could be seen as contributing to SSM (Figure 6). Note that the aspects of soil quality shown in Figure 6 are closely related to the soil threats identified earlier (Section 3.3).

In their global systematic review of the literature published between 1994 and 2022, Sharma *et al* (2023) identified 8 broad categories of SSM practices into which they allocated the various measures and techniques reported (Table 1). The authors noted that the majority of the studies reported were from cereal-based farming systems, thus SSM measures specifically related to grassland or horticulture systems are unlikely to have been represented in their summary tables and discussion. Additionally, because the authors reviewed the global literature, some of the identified SSM measures may not be relevant in the context of UK agricultural systems.

			Organic matter	Biodiversity	Compaction	Erosion		Pollution	Nutrient balance	Salinisation
						Wind	Water			
Land use, land-use change	Afforestation, deforestation and maintenance of forest	Grassland -> forest	0/-							
		Arable -> forest	++	++	++	++	++	++	+	+
		Forest -> arable	-	-	-	-	-		-	
		Forest (long-term maintenance)	++	++	++	++	++	++	++	++
		Agroforestry*	++	++		++	++	++	++	
	Creation, loss and maintenance of grasslands	Forest -> grasslands	0/-							
		Arable -> grasslands	++	++	+	++	++	+	++	
		Grasslands- > arable	-	-	-	-	-	-	-	
		Maintenance of grasslands	++	++	++	++	++	+	++	
	Wetlands management	Creation or restoration of wetlands	++	++	-			++		
		Maintenance of natural wetlands	++	++	++			++		
		Drainage of wetlands	-	-			-		-	
	Other landscape elements	Landscape features	++	++		++	++	++	++	
		Buffer strips	++	++		++	++	++	++	
		Grass strips	++	++		++	++	++	++	
		Short rotation coppice	+	++		++	++	++		
	Operations	Terraces				++	++			
		Drainage	-	+/-	+		+			++
Management practices	Tillage and traffic management	Tillage	+	-	+/-	-	-			++
		Reduced tillage and No-tillage*	+	++/-	+	++	++	+/-		
		Late tillage								
		Subsoiling		-	++/-	-	-			++
		Ploughing**	-	-	+	-	-			++
		Use of heavy machinery			-					-
		Controlled traffic			+					+
	Soil cover and crop management	Diversified crop rotation*/**	+	+	++	++	++	++		
		Intercropping	++	+	++	++	++		++	++
		Cover crops*	++	+	++	++	++			++
		Catch crops	++	0	++	++	++		++	++
		Mulching*	+	++/-	++	++	++			++
		Maintenance of crop residues (no burning)*	++	++/-	++	++	++			++
		Nitrogen-fixing crops*/**	++	0					++	++
		Land lying fallow	+	+	+	++/-	++/-			
		Contour farming				++	++			
	Grassland management	Extensive grazing**	++	+				0/-		
		Intensive grazing	-	-	-	-	-	0/-		
	Pest/weed, diseases and fertilisation management	PPP application*		-				-		
		Mineral fertilisers application	++/-	+/-				-	++/-	+/-
		No synthetic pesticides/herbicides and no mineral fertilisation**	++	++	+	++/-	++/-	++	++	++
		Manuring	+	++/-	++			++/-	+	++
		Compost application	+	++	++			++/-	+	++
		Gypsum application								++
	Water management practices	Irrigation								+/-
	Forest management practices	Physical preparation for afforestation or reforestation	+/-	-	+/-	-	-			
		Prescribed burning	-	-	-	-	-		+/-	
		Clear felling	-	-	-	-	-		-	
		Whole tree harvesting techniques	0/-	-	-	-	-		-	
		Maintenance of forest residues	++	++/-		++	++			
		Harvest compensation application techniques							+	

Positive impact: ++, +; **Negative impact**: -; **Impact depending on the context**: +/-, 0/-; **Empty cells**: no relation found in the literature; *: **Practices associated with conservation agriculture**. As this farming system is not regulated by the EU, the practices implemented can vary depending on farms. **: **Practices associated with organic farming** as regulated by the EU.
Source: Alliance Environnement, based on existing literature

Figure 6. Effects of agricultural activities on aspects of soil quality (EEIG Alliance Environnement, 2020)

Table 1. SSM categories and measures identified by Sharna *et al.* (2023).

SSM category	SSM measure
Minimum soil disturbance	No tillage; minimum/reduced/conservation/non-inversion/zero tillage
Residue management	Crop residue incorporation
Use of manure	Organic manure/fertilisers, farmyard/green/animal manure, compost
Soil cover	Cover crop, mulching, permanent soil cover, grass cover
Crop rotation	Crop rotation with legumes and other crops
Strips/barriers/bunds	Contour vegetative strip, contour barriers, construction of soil bunds, living barriers, terraces/stone walls, napier grass/bench terraces, grass strips, hedge rows, integration of vetiver grass, cultivation of less-erosive crops (horse beans, field peas, lentils, chickpeas, and rough peas), terrace reinforcement plants
Intercropping	Intercropping, alley cropping, legume intercropping, mixed-cropping techniques
Agroforestry	Integrated cropping and livestock system, trees/shrubs grown within crops

In Germany, Techen & Heling (2017) reported results from a review of 267 documents looking at drivers and trends in soil management from the perspective of sustaining soil functions (Figure 7). They concluded that consumer demand in combination with new technologies, research, and the change in farmers' attitudes were the strongest drivers towards improved soil management. Policies were not irrelevant, but they did not show strong trends towards or against SSM. Changes in soil management practices that were assessed to impact soil function (positively or negatively) included:

- Field sizes, field patterns and transition zones
- Intercropping and agroforestry
- Integration of lignocellulosic crops (i.e. biomass crops)
- New crop varieties (for climate change and pathogen resistance)
- Crop rotations: diversity, cover crops and legumes
- Reduced tillage
- Subsoil management
- Machinery weight and contact stress
- Precision application of fertilisers and pesticides
- Restrictions on pesticide use
- Organic material inputs
- New fertilisers from recycled nutrients
- Soil/seed inoculation for pest control
- Irrigation

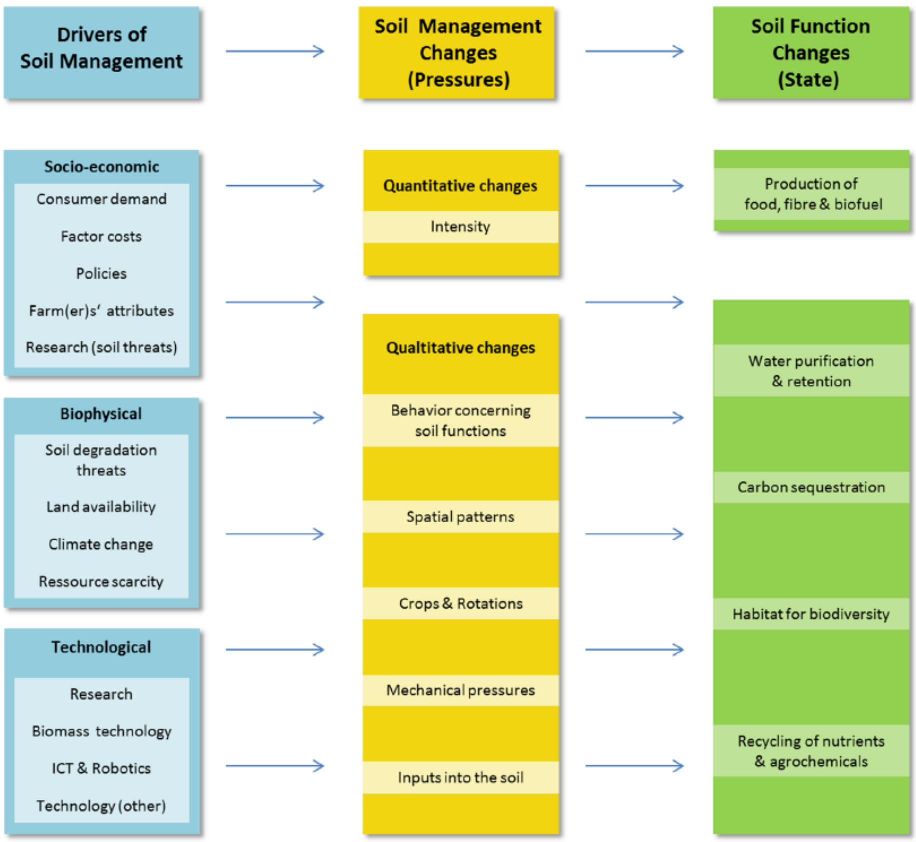

Figure 7. Drivers of soil management. Techen & Helming (2017)

Building on this framework, another research team (Strauss *et al*, 2023) screened stakeholder documents from public governance institutions, nongovernmental organizations, the agricultural industry, and conventional and organic farmer associations for recommendations related to agricultural soil management in Germany. A total of 46 recommended SSM measures were identified, from which a shortlist of the seven most commonly referenced measures was derived (i.e. those used in over 1/3 of stakeholder documents; Table 2). Taken together, the authors concluded that these measures supported all agricultural soil functions and addressed all major soil threats, apart from soil contamination (Figure 5). Although not explicitly stated in the paper, most of the SSM measures in Table 2 generally relate to arable farming systems, with few being of direct relevance to grassland or horticulture. Interestingly, soil related training for farmers was identified as a SSM measure (although it was not shortlisted).

Table 2. SSM measures identified in German stakeholder documentation (Strauss *et al.*, 2023).

Shortlisted SSM measures	Other SSM measures (related to spatial patterns)	Other SSM measures (related to crops and rotations)	Other SSM measures (related to mechanical pressures)	Other SSM measures (related to soil inputs)	Other SSM measures (related to farming system)
• **Including structural landscape elements/ biodiversity refuges** • **Organic fertiliser use** • **Diversified crop rotations** • **Permanent soil cover** • **Conservation tillage** • **Reduced soil loads** • **Optimised timing of wheeling**	• Contour farming • Cross slope barriers • Site adapted field sizes • Appropriate drainage • Greening tramlines/ natural depressions • Set aside of marginal sites • Set aside of erosion sensitive sites • Tillage direction transversely to wind direction	• Pathogen resistant varieties • Climate adapted varieties • Legume rich crop rotation • Short rotation coppice • Paludiculture	• Reduced/alternating plough depth • Reconsolidation after soil loosening • No spring plough • Rough soil surface • Reduced wheeling frequency • Wheeling in tramlines • Optimised traction transmission • On land ploughing • Soil-related training for farmers	• Site specific liming • High precision fertiliser/pesticide application • Precise fertiliser demand estimation • Integrated pest management • Coated seeds • No uncertified pesticides • No broad-spectrum herbicides • Closed nutrient cycles • No untreated/ contaminated organic amendments • No uncertified fertilisers • Pathogenic antagonists • Microbial inoculants • Irrigation efficiency improvement • Monitoring irrigation water quality	• Mixed cropping systems • Agroforestry • Organic farming

A Spanish study by Tepes *et al* (2021) reviewed information from 26 scientific papers and technical reports from selected European countries, focussing primarily on arable croplands. Data was gathered into a database of 22 different soil protection and sustainable land management practices grouped into broad categories (Table 3). The authors went on to propose a new multidisciplinary approach for an economic assessment of soil protection practices at the farm level.

Table 3. Soil protection practices identified by Tepes *et al*. (2021).

Category	Practice
Soil management	Cover crops De-compaction Direct tillage Mulch sowing Reduced tillage Zero tillage Tramline management Reduced stocking density Fertiliser management
Systems	Agroforestry Erosion control: Buffer zone and crop rotation
Vegetation management	Crop rotation Crop varieties High density planting and narrow spacing Intercropping and catch crops Timeliness Vegetated buffer strips
Water management	Contour ploughing Cultivation perpendicular to slope gradient Earth banks, swales and sediment traps Irrigation
Infrastructure	Land use change

A European Joint Programme (EJP) SOIL study of agricultural soil management in Europe (Keestra *et al*., 2023) included a consultation with soil stakeholder groups including academics, policymakers, NGO's and farmer organisations or farmers. The feedback from this consultation indicated that whilst there are a range of soil management solutions of potential benefit for the sustainability of agro-ecosystems and the natural environment, there are still many uncertainties and knowledge gaps over their exact impacts and the context within which each management option would be most effective. Five specific requirements were identified:

i) Develop soil monitoring programmes and modelling studies to support sustainable management decisions at a site-specific level under different climate-change scenarios;
ii) Develop site-specific, precision agro-ecological practices to improve soil ecosystems;
iii) Evaluate farm level drainage systems to minimise environmental impacts;
iv) Study the cost-effectiveness and applicability of soil improving practices from a farmer's point of view;

v) Assess costs and benefits of management practices when quantifying their potential for sustainable agricultural systems;
vi) Develop analytic approaches (laboratory or experimental fields) and farm scale to assess differences between controlled and real-life conditions.

The authors stressed that a holistic approach to SSM is needed as soil issues are complex and interrelated with wide societal concerns (Figure 8).

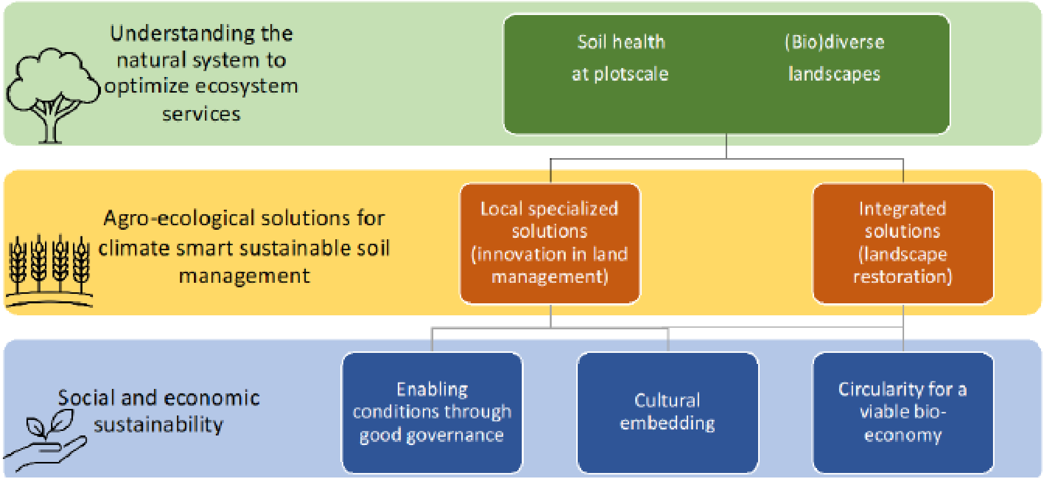

Figure 8. Three layers for sustainable soil management: the biosphere: healthy soils and (bio)diverse landscapes (green bar); solutions: based on functioning of the natural system (yellow bar); enabling conditions: finding social and economic enabling conditions (blue bar). Keestra *et al* (2023)

One of the few sources to focus on SSM measures for grassland soils was McTavish *et al.* (2021). In this book chapter the authors explain that grasslands have been extensively managed and exploited, and face major threats including land use change, climate change, woody encroachment, and biological invasion. Their research and knowledge synthesis found that the primary tools used to sustainably manage grassland soils include prescribed fire, grazing and mowing management, and application of soil amendments (including inorganic or organic fertilisers and lime), although few details are given apart from the fact that these measures require proper planning and appropriate application. The authors conclude that best practices for sustainable management of grassland soils are highly context specific and there is no ‘one size fits all’ approach that can be taken.

4.2. SSM measures identified from UK literature sources

4.2.1. Peer reviewed literature

A survey of current SSM practices in the UK and a discussion around how they relate to the principles of regenerative agriculture was recently published by Jaworski *et al.* (2023). The authors established a list of the 14 most recognised and implemented SSM practices in the UK based on a review of current SSM policies and advice (i.e. from Defra, the Soil Association, NIAB) validated in consultation with a panel of soil scientists. These were then classified by the five principles of regenerative agriculture (Table 4).

In this study, different types of organic materials were treated as different SSM measures, but biosolids were not included although they are commonly recycled to agricultural land in the UK. The study also focussed mainly on arable soils and rotations, with mob grazing being the only measure specifically related to grassland soils.

In their paper on agricultural practices most likely to deliver "sustainable intensification" in the UK, Dicks *et al*. (2018) identified four priority practices relating to soils as follows:

- Reduce tillage to minimum or no till
- Incorporate cover crops, green manures and other sources of OM to improve soil structure
- Plant legumes—includes peas and beans, for forage and other products
- Controlled traffic farming to minimise soil compaction and energy use

Table 4. Classification of SSM practices according to regenerative agriculture principles. Note that some practices contribute to more than one principle (e.g. leys, cover crops), whilst some do not correspond to a regenerative agriculture principle (e.g. adapting ploughing to topography). From Jaworksi *et al*. (2023)

Regenerative agriculture principle	**SSM practices**
Minimize soil disturbance	No-tillage,
	Minimum-tillage,
	Leys (including herbal leys)
Maximize crop diversity	Diversified rotation (four or more crops within a 6-year period, excluding cover crops)
	Leys (including herbal leys)
	Growing legumes
	Cover crops
Keep soil covered all year round	Cover crops
	Leys (including herbal leys)
	Overwinter stubble,
	Returning all crop residue to the field
Maintain living roots all year round	Cover crops
	Leys (including herbal leys)
Increase SOM through the use of non-chemical fertilizers:	Using compost
	Using slurry,
	Using digestate,
	Using manure,
	Returning all crop residue to the field
	Leys (including herbal leys)
	Mob/holistic grazing
	Adapting ploughing to topography (e.g. contour ploughing).

The literature searches also returned papers which addressed specific soil threats. For example, Boardman *et al.* (2017) listed several practices which had been implemented by farmers to change the erosion risk on sites of former serious erosion in the South Downs National Park.

- Arable reversion to permanent grassland
- Overwinter stubble
- Buffer strips
- Beetle banks

- Working across slope
- Minimum tillage
- Timing of operations (ploughing, sowing etc)
- Adding OM
- Avoiding compaction on headlands
- Leaving seedbeds rough
- Avoiding rolling
- Changing roller
- Rolls
- Changing cropping patterns
- Earthworks built or modernized

Similarly, in their report on soil erosion and compaction in Scottish soils, Lilly *et al.* (2018) found a link between soil compaction and erosion. Soils that become compacted have less capacity to store rainfall and therefore generate erosive overland flow more quickly than non-compacted soils. The greatest driver of soil compaction was found to be machinery weight, which has been increasing over the past few decades, although using wide tyres, dual wheels and low-pressure tyres can reduce the impact. An earlier review of soil compaction and soil management (Batey, 2009) concluded that compaction tended to be more severe when root crops and vegetables were harvested from wet soils close to field capacity. Bhogal *et al*. (2018) estimated that 40-60% of agricultural soils in the UK are in 'moderate' condition (i.e. show evidence of some structural degradation' and up to 30% in poor condition (or severely degraded), with traffic and tillage pans widespread within arable and horticultural systems. They recommended that soil management should include methods to improve resilience (e.g. by improving SOM levels), avoid or limit damage (using low ground pressure types or controlled traffic) and to alleviate compaction where it occurs (typically by using subsoilers/sward lifters).

Some papers were identified which focussed on specific SSM measures such as liming, whilst other practices which are known or claimed to beneficially impact soil properties (e.g. biochar applications and the use of soil microbial inoculants) were not highlighted in the literature searches.

4.2.2. Grey literature

Other sources of information include the 'Best Practices for Soil Organic Matter (SOM) Management in Lowland Agriculture' report produced as part of Defra project SP08016 (Bhogal *et al*, 2009). Focusing largely on UK studies and reviews, measures that potentially benefit SOM were identified and summarised, taking into account variations in soil type, agricultural systems and cropping/land-use wherever possible, as well as considering the relative costs, benefits and environmental impacts. The methods identified were classified into broad categories as shown in Table 5.

An AHDB-funded study aimed to develop an industry recognised method for assessing grassland soils and to provide guidance on soil biology, culminating in the production of the 'Healthy Grassland Soils' pocketbook (AHDB, 2023). This provides advice on compaction alleviation and reseeding and outlines various compaction avoidance measures, namely:

- Keep livestock off wet fields after heavy rainfall to avoid poaching, damaging the upper layer of the soil and reducing sward density; higher stocking densities can increase soil compaction
- Increase grazing rotations, particularly in wet conditions
- Strip graze with a back fence

- Ensure a good network of farm tracks and multiple gateways
- Site drinkers/feeders to avoid compaction. Move temporary drinkers/feeders regularly.

Table 5. Practices that benefit SOM (from Bhogal *et al*., 2009).

Category	Practice
Land-use change	• Convert tillage land to permanent grassland • Establishment of permanent field or riparian buffer strips • Establish permanent woodlands • Establish farm woodlands/hedges • Grow biomass crops (i.e. willow, poplar, miscanthus) • Introduce rotational grass • Water table management
Reduce soil erosion	• Take action to reduce soil erosion on tillage and grassland • Cultivate compacted tillage soil • Leave autumn seedbeds rough • Cultivate across the slope • Manage over-winter tramlines • Early establishment of winter crops • Fence off rivers and streams from livestock • Move feed/water troughs at regular intervals • Loosen compacted soil layers in grassland fields • Reduce stocking density
Change tillage/ cultivation practices	• Adopt reduced or zero tillage systems
Increase OM additions/returns	• Autumn establishment of cover crops or green manures • Incorporation of straw/crop residues • Encourage use of livestock manure • Import materials high in organic carbon
Speculative methods	• Convert to organic farming systems • Extensification of pig and poultry systems onto arable land • Place OM deeper in soil • Use clover in grassland (mixed sward) • Reduce use of lime on grasslands and organic/peaty soils • Minimise fertiliser use on organic soils

Also funded by AHDB, a survey of farmers practising regenerative agriculture in the north of England (Magistrali *et al*., 2022).) identified a list of regenerative agriculture activities (adapted from Giller *et al*., 2021).

- Zero-till (less than 10% of soil moved)
- Reduced tillage (Defra define as up to 5 inches of soil cultivated, essentially no ploughing)
- Controlled traffic
- Mulching (organic residues spread around or over plants to enrich or insulate the soil)
- Cover crops / green manures
- Use of biochar
- Use of farm animal manures/compost

- Use of farm animal slurry
- Compost tea (a nutrient rich liquid made by combining compost with water)
- Inoculation of soils and composts
- Agroforestry/silvo-pasture (integrating trees, forage, and the grazing of domesticated animals in a mutually beneficial way)
- Tree crops
- Maintain diverse crop rotations
- Rotational grazing
- Mob grazing (rotational grazing BUT with longer "rest" periods and removing stock with grass less severely grazed)
- Herbal rich ley

These were refined into a list for the survey where farmers selected which of the 12 activities they associated with regenerative agriculture (Figure 9).

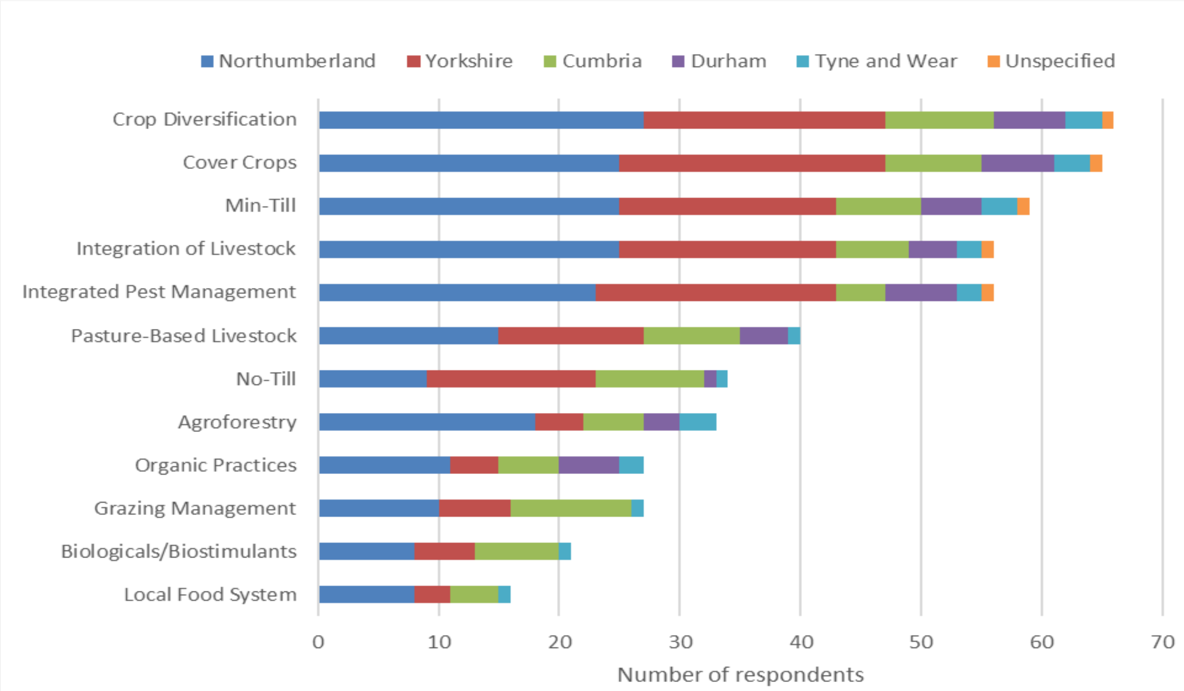

Figure 9. Practices that farmer survey respondents associate with regenerative agriculture (Magistrali *et al.*, 2022**)**

Burgess *et al.* (2023) identified 16 agroecological practices that could be used in the UK: many of which correspond to SSM measures or have implication for SSM. These were: crop rotations, conservation agriculture, cover crops, organic crop production, integrated pest management, the integration of livestock to crop systems, the integration of crops to livestock systems, field margin practices, pasture-fed livestock, multi-paddock grazing, organic livestock systems, tree crops, tree-intercropping, multistrata agroforestry and permaculture, silvopasture, and rewilding.

5 REVIEW OF SSM MEASURES USED IN THE UK

A list of SSM measures was compiled from those identified in the literature reviewed in Sections 4.1 and 4.2 above, focussing on measures that are currently used or could potentially be used in UK farming systems. These were supplemented, where appropriate, using the project team expertise to fill in any gaps not addressed by the literature reviewed (for example, SSM measures related to grass and grazing management were not well covered in the literature). To aid with the review process and SWOT analysis, the measures were assigned to broad categories based on those identified by Strauss *et al* (2023), i.e. Soil Inputs, Grass and Grazing Management, Crops and Rotations, Mechanical Pressures and Physical Environment. The project team identified an additional broad category of SSM measures relating to soil testing and monitoring, and education and advice. Although these topics were identified by UN (2016) in their principles of SSM, they were not well addressed in the SSM literature reviewed here, despite being of key importance if the goal is to achieve SSM. A final category of novel/untested SSM practices was created to capture measures which had been identified in some of the literature reviewed as potentially contributing to SSM, but which are not currently widely used in the UK for SSM either because of the lack of supporting scientific evidence for their beneficial effects or because they have not been subject to field trials and testing under UK conditions.

Broad farming systems or approaches were not included as SSM measures e.g. organic farming, rewilding, conservation/regenerative agriculture as these may encompass some or all of the individual SSM practices identified. It was not the aim of this review to endorse or otherwise particular approaches to farming, although it was possible to identify various SSM measures that need to be adopted as part of certification schemes e.g. organic/biodynamic certification.

For each measure, a brief evidence review was compiled summarising the scientific information available to support the beneficial (or otherwise) effects of that measure on soils. These were not intended to be comprehensive subject reviews, but aimed to describe the quantity and quality of scientific evidence available and to identify any key (review) papers or important new research, with the focus on UK-based work. These were supplemented with lists of the legislation, government/voluntary schemes and advice that mention or promote each measure. A summary table for each broad category of SSM measures, included the relevance of each measure for arable, grassland or horticultural land uses, the main soil threat(s) addressed, and the main benefits and risks/issues associated with the practices (Tables 6-10).

Notes:

- Many of the SSM measures identified here are the same as those for reducing diffuse pollution from agriculture (e.g. Collins *et al.* 2018). This is because sediment and nutrient losses which lead to pollution of watercourses are (usually) associated with soil loss from fields (i.e. soil erosion) which is one of the main threats to UK soils (see Section 3.3).
- Similarly, many SSM measures mirror those identified by Bhogal *et al*. (2009) as practices to manage SOM in agriculture. Any measure that aims to conserve or improve SOM levels will also improve a range of soil physical, chemical and biological properties and hence will improve soil structure and stability reducing the threat of compaction and erosion (see for example Section 5.1.1).
- Very few papers had studied the impact of grass/grazing management on SSM. The measures identified in Section 5.2 were therefore largely based on previous work undertaken by the Project Team. What constitutes an appropriate and effective SSM measure will vary

depending on a range of agroclimatic factors. Some measures may not be appropriate for all farming systems, or may only be appropriate under particular soil/climate conditions.

5.1. SSM measures relating to soil inputs.

5.1.1. Apply organic materials (livestock manure, compost/digestate, biosolids).

Brief evidence review

There is general agreement across all the papers identified in the literature review that applying organic materials is an effective SSM method to address the threat of SOM loss. There is a very large body of evidence collated over many years (from the UK and elsewhere in the world) on how applications of organic materials of various types can increase SOM and at the same time improve other measures of soil health such as nutrient supply, soil structure, bulk density, water holding capacity, microbial biomass and earthworm numbers, and reduce erosion and compaction risks (see, for example; Johnston *et al*., 2009; Powlson *et al*., 2012; Smith *et al*., 2015; Whitmore *et al.,* 2017; Bhogal *et al.,* 2018). A good summary of the benefits (and disbenefits) of biosolids applications is given in Nicholson *et al.* (2022) and on the effects of digestate and compost on soil quality in WRAP (2015).

Whilst contaminant levels and soil addition rates in biosolids, composts and digestates are tightly controlled (see below) there is currently no regulation of contaminants (e.g. PTEs) in livestock manures, although the Code of Good Agricultural Practice (COGAP; Defra, 2009)[7] states that farmers should "Monitor the metal content of the soil whenever organic manures, waste materials, or metal containing pesticides are applied regularly." New research from a team of EU authors reviewed 407 papers and showed that livestock manure quality (i.e. its PTE, hormone and antibiotic content) was more important than manure quantity for promoting soil biodiversity and recommended more targeted policies to control this (Koninger *et al*, 2021). Another potential issue is that certain areas of the country (e.g. parts of northwest England) support much higher numbers of livestock and have manure (and hence nutrient) surpluses, whilst arable areas in the south and east are highly reliant on imported manures. There will also be regional difference in the availability of other organic materials.

Summary of relevant legislation and government schemes (England)

- All organic materials must be applied according to the **FRfW** (SI, 2018).
- For farms in NVZs (which cover c. 60% of agricultural land in England) applications must comply with the **Nitrate Pollution Prevention Regulations** (SI, 2015; 2016) to minimise diffuse pollution losses. Farmers should follow good practice guidelines when spreading to avoid soil damage (see Section 5.1.2).
- Additional regulations apply to biosolids. **The Sludge (Use in Agriculture) Regulations** (SI, 1989) restrict the quantities of PTEs that can be applied to land from biosolids. The regulations place legally binding limits on the amounts of zinc, cadmium, lead, copper, chromium, mercury and nickel in biosolids that can be applied. The regulations also provide maximum soil PTE concentrations above which biosolids cannot be applied. The Regulations are complemented by the **Code of Practice for the Agriculture Use of Sewage Sludge** (The Sludge Code; DoE, 1996)[8] which set lower soil limits for some PTEs, and in addition provide recommendations on maximum loading rates for molybdenum, arsenic, selenium and fluoride.

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[7] Henceforth referred to in this report as the COGAP

[8] Henceforth referred to in this report as The Sludge Code

- Some organic materials (e.g. dairy processing wastes) can be applied to land under an exemption from the **Waste Management (England and Wales) Regulations** (SI, 2006a), which state that 'waste' can only be applied to agricultural land where such treatment results in benefit to agriculture or ecological improvement.
- For compost and anaerobic digestate applications applied under the respective Quality Protocols (i.e. no longer treated as wastes; WRAP/EA, 2012; WRAP/EA, 2014), the contaminant limit values set in **PAS100** and **PAS110** should not be exceeded, neither should the PTE limit values in the receiving soil (as set in the Sludge Code of Practice) be exceeded.
- **SFI**: NUM1 aims to optimise use of organic sources of crop nutrition; SAM1 relates to assessing soil, producing a soil management plan and testing SOM.

Summary of voluntary schemes and initiatives (England)

- The **Biosolids Assurance Scheme** brings together the legislative and Sludge Code controls on biosolids recycling into one independently audited standard which has been adopted by the Water Industry. This standard includes all the restrictions on biosolids use included in the guidance and regulations.
- **Scottish Quality Cereals** and the **Scotch Whisky Association** will not accept malting barley which has received applications of biosolids or PAS110 digestate.
- The **Soil Association** states that in organic agricultural systems plants must be nourished primarily through the soil ecosystem including by the application of livestock manure or organic material preferably composted and from organic production. Information is required on the description, compositional requirements and conditions of use for permitted fertilisers, soil conditioners and nutrients. For example, non-organic manure must not be from factory farming origin or contain GM ingredients, and liquid animal manure must undergo controlled fermentation and/or appropriate dilution before use. Records of fertiliser and soil conditioner inputs must be kept.
- **Certified Regenerative** state that crop residues and manure must be added back to the soil when available.
- **Regenagri** sets out natural fertiliser strategies for yield optimization, improved fertiliser efficiency, increased biodiversity and SOM and avoiding nutrient leaching; these can include organic fertilisers, compost, manure digestates, or any other compound derived from nature without the need for synthetic processing.
- **Pasture for Life** encourages integrating livestock into arable systems and using livestock manure to build fertility (see Section 6.2.9)**.**
- **Biodynamic Certification** organic production standards contain information on allowed manures and plant wastes, together with rules regarding their management and application.

Examples of relevant advice and guidance

- The **Biosolids Nutrient Management Matrix** (ADAS, 2014; Chambers *et al*., 2013) advises on the frequency of biosolids applications based on the soil P index.
- The **COGAP** (Defra, 2009) recommends taking positive action to maintain or increase SOM to improve soil stability and increase workability; methods include applying bulky organic manures. It also states that farmers should "Monitor the metal content of the soil whenever organic manures, waste materials, or metal containing pesticides are applied regularly."

- **CFE** suggests that SOM can be maintained through returning manures or adding off-farm OM such as sludges, digestates and composts.

5.1.2. Optimise timing/amount/method of organic material applications.

Brief evidence review

Optimising the timing, amount and method of organic material applications will improve nutrient use efficiency (NUE), by minimising nutrient losses to the environment and reducing the need for mineral fertiliser applications to meet optimum crop requirements. There is again a very large body of field experimental evidence from the UK and elsewhere on how and when to apply organic materials to minimise nutrient losses via nitrate leaching or phosphorus runoff (e.g. ADAS, 2007; Withers *et al.,* 2014; Withers *et al*. 2017; Kleinman *et al*., 2015; Ockenden *et al*., 2017 and many others), and ammonia and nitrous oxide emissions to air (e.g. Beltran *et al*., 2020; Bell *et al*., 2016 and many more). This evidence has been collated, extensively reviewed and used to inform the regulations and guidelines now in place in the UK and EU.

Summary of relevant legislation and government schemes (England)

- All organic materials must be applied according to the **FRfW**.
- In NVZs, the **Nitrate Pollution Prevention Regulations** (SI, 2015; 2016. See Section 5.1.1) will minimise the risks of nutrient losses to water.
- **SFI**: NUM1-3 specifically relate to nutrient management focussing on increasing nutrient management knowledge, supporting more efficient use of nutrients and encouraging more effective use of organic sources of crop nutrition. A nil fertiliser supplement is payable in some situations.

Summary of voluntary schemes and initiatives (England)

- **LEAF Marque** requires the creation of a manure management plan and sets out the recording of organic/inorganic fertiliser applications and the importance of nutrient management.
- **Certified Regenerative** requires farmers to use manure, soil improver, and fertiliser application techniques to minimise the loss of nutrients and leaching.
- The **Soil Association** requires certified organic farms to have an agreed plan for spreading manure together with a full description of the areas given over to crop production, and where appropriate, as regards the spreading of manure, any written arrangements with other holdings.
- **Biodynamic Certification** organic production standards contain information on allowed manures and plant wastes, together with rules regarding their management and application.
- **Pasture for Life** requires all farms to have a pasture management plan including nutrient management (with fertiliser/manure application targets).

Examples of relevant advice and guidance

- The **COGAP** (Defra ,2009) provides advice on manure and nutrient management plans, and on the application of livestock manures and other organic wastes. Abiding by good practice guidelines will minimise nutrient losses to the wider environment and protect the soil from damage during spreading.

- The **Code of Good Agricultural Practice for Reducing Ammonia Emissions** contains guidance on applying organic manures effectively and efficiently.
- Good practices guidance for using organic materials based on many years of research and expert knowledge is provided in **RB209** (AHDB, 2019).
- **CFE** provides several recommendations for optimising nutrient management including selecting best practice application methods to match manure/organic material and soil types.

5.1.3. Apply lime.

Brief evidence review

Whilst not mentioned specifically in the literature as an SSM method, liming soils is a well-established method for increasing soil pH and controlling acidification. In his review of the importance of liming agricultural soils, Goulding (2016) described how liming to recommended soil pH values not only increases productivity, but also improves soil structure and degraded soils, and can benefit grassland biodiversity if managed appropriately. It also reduces some GHG emissions (e.g. N_2O), although CO_2 will be emitted when lime reacts with soil acidity. Later reviews by Holland *et al.* (2018) and Eze *et al*. (2018) reiterated the benefits of liming for arable and grassland productivity, and herbage quality, but noted that it can take a considerable time to detect any changes in soil physical properties. A review of soil acidity and liming undertaken for AHDB (Tripney *et al*., 2021) again stressed the benefits of applying lime, and also pointed out that it can alleviate aluminium toxicity in plants growing on acidic soils.

Additional beneficial effects include short-term impacts on soil biota. For example, it is known that earthworms are very sensitive to soil pH, although the effect is species dependent with some species intolerant to acid soils whilst others thrive in it (Edwards & Arancon, 2022). Liming can affect some soil biological processes increasing crop N and P availability and can also decrease the availability of (some) PTEs. Impacts on soil C storage are variable and depend on soil type, land use, climate and multiple management factors. For example, Eze *et al* (2018) reported that whilst lime (and fertiliser) use on grasslands could lead to greater production of root exudates and litter, there may be unintended effects on soil microbial decomposer populations with implications for soil C storage and sequestration. There is some evidence that *decreasing* the use of lime on grassland or peaty soils could increase SOM levels by decreasing OM decomposition rates (see Bhogal *et al.*, 2009).

Summary of relevant legislation and government schemes (England)

- For biosolids applications, the soil limit values for zinc, copper and nickel defined in the **Sludge Use in Agriculture Regulations** and the **Sludge Code of Practice** are pH dependent, such that at higher soil pH, greater soil PTE concentrations are permitted.

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** and **Biodynamic Certification** schemes provide specific information on the description, compositional requirements and conditions of use for permitted fertilisers, soil conditioners and nutrients. For example, calcium carbonate (lime) must be of natural origin.

Examples of relevant advice and guidance

- Recommendations on soil pH and liming for arable and grass systems based on many years of research and expert knowledge is provided in **RB209** (AHDB, 2019).

- The **COGAP** (Defra, 2009) provides advice on lime and manufactured fertiliser application.
- Advice on optimising soil pH is given in the **AHDB Beef and Sheep Manual 3** (Improving soils for Better Returns)
- **CFE** suggests that nutrient management can be optimised by maintaining pH (although no pH values are specified). Regular soil testing to optimise fertiliser and lime use (pH, P, K, Mg) is also recommended.

5.1.4. Apply gypsum.

Brief evidence review

Gypsum application is mentioned in several of the literature sources as a method to regulate soil acidity (e.g. FAO, 2017) and improve soil structure (EEIG, 2020), although it is not a liming agent and only has a minor effect on soil acidity (SEPA, undated). It is however high in sulphur which is an important nutrient for some crops such as grass and oilseed rape (Sagoo *et al*., 2018a). It can improve soil structure in some circumstances (i.e. in areas flooded by sea water) and can promote root development (e.g. Zoca & Penn, 2017; Dick, 2018).

Summary of relevant legislation and government schemes (England)

- Recycled gypsum from waste plasterboard can be applied to agricultural land providing it meets **PAS109** standards and the requirements of the QP (EA, 2015) to avoid soil PTE contamination. In addition, the Environment Agency have issued low risk position guidance for storing and spreading gypsum waste to benefit land (**LRWP59**) without a permit.

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** and **Biodynamic Certification** schemes provide information on the description, compositional requirements and conditions of use for permitted fertilisers, soil conditioners and nutrients. For example, calcium sulphate (gypsum) must be of natural origin.

Examples of relevant advice and guidance

- None

5.1.5. Apply mulch.

Brief evidence review

Mulching with organic materials not only provides a source of OM to soils, but also helps to retain soil moisture and protects otherwise bare soil from the risk of erosion; it is mentioned by several literature sources as a SSM practice. In a cost-benefit analysis, Posthumus *et al.* (2013) found that mulching was one of the most cost-effective erosion control measures for agriculture in the UK. Mulches such as straw and composted green waste also act as a source of nutrients and should be accounted for in fertiliser planning. Plastic mulches (often used for soft fruits) will protect the soil from erosion and retain moisture, but will not supply OM and may also be a source of plastic pollution.

Summary of relevant legislation and government schemes (England)

- The **Nitrate Pollution Prevention Regulations** (SI, 2015; SI, 2016) control the amount and timing of N that can be applied in compost used as mulch.
- **SFI**: IPM3 refers to sowing a companion crop to form a living mulch beneath an arable or horticultural crop (see Section 5.3.7)

Summary of voluntary schemes and initiatives (England)

- **Regenagri** suggests that irrigation efficiency can be improved through mulching (see Section 5.1.7).

Examples of relevant advice and guidance

- The **COGAP** (Defra, 2009) suggests applying a surface mulch (e.g. farmyard manure) to limit the effects of wind erosion on light or other blowing soils.

5.1.6. Return straw/crop residues.

Brief evidence review

Returning straw and other crop residues to the soil after harvest (as opposed to removal or burning) is a frequently cited SSM practice and is widely practiced in UK agriculture. It has the potential to increase the SOM content of agricultural soils (Bhogal *et al.,* 2007) and acts as a source of nutrients, improving soil structure and providing benefits similar to those from livestock manure and other organic material applications (Nicholson *et al*., 2014). A recent review (Fu *et al*., 2021) reported how crop residues can be used to improve soil physical properties (by increasing soil moisture content, decreasing bulk density, and increasing total porosity and aggregate stability); alter soil pH, cation exchange capacity and microbial community composition; assist in soil remediation from PTEs and organic chemicals; and improve saline-alkali soils.

However, there are some circumstances when straw incorporation can cause short-term microbial immobilisation of N (Chen *et al*., 2023), which may lead to the need for additional mineral N fertiliser applications. Additionally, allelochemicals released during microbial decomposition of crop residues can have positive or negative effects on the following crop (Fu *et al*., 2021).

Summary of relevant legislation and government schemes (England)

- None identified

Summary of voluntary schemes and initiatives (England)

- **Certified Regenerative** standards state that crop residues and manure must be added back to the soil when available.

Examples of relevant advice and guidance

- **CFE** suggests that SOM can be maintained through incorporating crop residues.
- The **COGAP** (Defra, 2009) recommends taking positive action to maintain or increase SOM to improve soil stability and increase workability; methods include returning crop residues.

5.1.7. Optimise irrigation practices.

Brief evidence review

Improving irrigation practices was an SSM measure identified in several non-UK studies (see Figure 6, Tables 2 and 2) as a means to reduce the risk of soil salinisation. This is clearly of importance for farmers in drier climates and where irrigation is used extensively and water quality may be an issue. In the UK, irrigation is mainly used for horticultural crops and for high value root crops such as potatoes and carrots in arable rotations on light soils (i.e. in the drier east of England). Thus, in the UK where salinisation caused by irrigation is not usually an issue, improving irrigation water use efficiency may have a small effect on reducing nutrient losses and the risk of soil erosion, but this will only apply to certain crops, soil types and regions of the UK. However, as climate change continues to affect agroclimatic conditions and if drought periods become longer and more frequent, there may be a need to irrigate other crops (e.g. cereals, sugar beet), and salinisation may become a much greater potential future threat (see Section 5.8).

Summary of relevant legislation and government schemes (England)

- Taking water from wells, boreholes and reservoirs is regulated under the **Water Resources (Abstraction and Impounding) Regulations 2006** (SI, 2006) to ensure all users get a fair share and the environment does not suffer. The licensing and permit system is operated in England by the Environment Agency.
- The **FRfW** (SI, 2018) state that reasonable precautions must be taken to prevent significant soil erosion and runoff from land management and cultivation practices (including irrigation).

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** provides specific information on responsible use of energy, water and other natural resources. In relation to water use for irrigation and abstraction, farmers must identify areas prone to run off and soil erosion, and adopt strategies to minimise these.
- **Regenagri** state that one of their standard criteria is irrigation efficiency measures, including mulching (see Section 5.1.5).
- **Certified Regenerative** standards place importance upon farmland having effective water irrigation methods.
- **LEAF Marque** includes water management as part of their integrated farm management strategy.

Examples of relevant advice and guidance

- Advice on water management and crop irrigation is given in the **COGAP** (Defra, 2009).
- **Irrigation Best Practice Guides** for various crops are also available from ADAS.

5.1.8. Optimise agrochemical use.

Brief evidence review

Optimising the use of pesticides and herbicides was mentioned in several non-UK studies of SSM practices (see Figure 6, Table 2), although UK sources do not seem to have considered this to be an SSM measure *per se*. Methods identified for optimising agrochemical usage included integrated pest management (IPM), avoiding the use of broad-spectrum herbicides, using pathogenic antagonists and coated seeds.

Using agrochemicals can have a detrimental effect on soil fauna (e.g. Beaumelle *et al*., 2023) and microbial communities (e.g. Johnsen *et al.,* 2001). Optimising their usage by reducing or restricting applications may maintain and promote increased biodiversity in the soil itself and the surrounding environment, and contribute to improving overall soil health. Reduced trafficking from fewer agrochemical applications may also reduce the risk of soil compaction (see Section 5.4.2).

Summary of relevant legislation and government schemes (England)

- Pesticides are controlled under **Regulation (EC) 1107/2009** concerning the placing of plant protection products on the market (retained in English law after exiting the EU and their use is regulated by the Health and Safety Executive - HSE).

- **SFI**: IPM1-4 specifically relate to IPM. IPM3 deals with establishing a companion crop to protect soil and improve its condition (see Section 5.3.7)

Summary of voluntary schemes and initiatives (England)

- **Pasture for Life** warns against using herbicides stating that herbicide sprays can have a detrimental effect on diversity within pasture and diminish the mineral availability and nutritional value of the grazing.
- The **Soil Association** restricts the use of pesticides and plant protection products and specify conditions for their use and necessary reporting procedures.
- **Fair to Nature** requires that an IPM plan is maintained to reduce use of pesticides through appropriate use of techniques, including maximising the potential for natural pest control.
- **LEAF Marque** considers IPM to be one of the central tenets of integrated farm management and set out in detail how they think this should be covered.
- **Regenagri** includes synthetic pesticide reduction as one of their standard criteria.
- **Certified Regenerative** details herbicides and pesticides in their restricted materials. They state that use of herbicides or pesticides should be justified and a plan should be made to reduce usage and phase them out.
- **Biodynamic Certification** sets out which products are permitted.

Examples of relevant advice and guidance

- **CFE** recommends lengthening rotations to allow for soil-borne pest management.
- The **COGAP** (Defra, 2009) provides advice on pesticide application.

5.1.9. Optimise mineral fertiliser use.

Brief evidence review

Optimising the use of mineral fertilisers was identified as a SSM method by Smith *et al.* (2015). Optimising mineral fertiliser applications (singly or in combination with organic material applications) will contribute towards closing nutrient cycles and reducing diffuse pollution (by minimising losses to air and water), and contribute to SOM by increasing the amount of crop residue returns (Smith *et al*., 2015; Section 5.1.6). Some mineral fertilisers can contain elevated PTE concentrations (e.g. cadmium in phosphate fertilisers) and other contaminants (e.g. Deleebeeke *et al*., 2021) so that avoiding unnecessary or over-application will also reduce the risk of soil contamination.

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) set out circumstances when mineral fertiliser use is prohibited.
- The **Nitrate Pollution Prevention Regulations** (SI, 2015; 2016) control the application timing and rate of N fertilisers in Nitrate Vulnerable Zones.
- The **EC Fertiliser Regulations (**EC, 2019) set out harmonized limit values on the amounts of cadmium (and other contaminants) that are allowed in fertilising products to minimise present and future adverse health and environmental effects.
- **SFI**: NUM1-3 specifically relate to nutrient management focussing on increasing nutrient management knowledge, supporting more efficient use of nutrients and encouraging more

effective use of organic sources of crop nutrition (see Section 5.1.2). A nil fertiliser supplement is payable in some situations.

- **Countryside Stewardship**: SW14 allows a nil fertiliser supplement to be paid in certain circumstances.

Summary of voluntary schemes and initiatives (England)

- **Pasture for Life** states that artificial fertilisers must only be used when nutrient management planning indicates a need that cannot be met by composts, manures, or green manures. Scheme users must have a pasture management plan that include nutrient management with fertiliser application targets.
- The **Soil Association** state that in organic agriculture plants must be nourished primarily through the soil ecosystem rather than with mineral fertilisers (see Section 5.1.1). They contain specific information on the description, compositional requirements and conditions of use for permitted fertilisers, soil conditioners and nutrients. Records of fertiliser and soil conditioner inputs must be kept.
- **Fair to Nature** requires that steps be taken to minimise the use of inorganic N fertiliser.
- **LEAF Marque** standards set out the recording of organic and inorganic fertiliser applications and the importance of nutrient management.
- **Certified Regenerative** requires farmers to use "Manure, soil improver, and fertiliser application techniques to minimise the loss of nutrients and leaching".
- **Regenagri** encourages the reduction of synthetic fertiliser use in order to boost soil biology, increase nutrient cycling, and avoid nutrient leaching and watershed pollution.

Examples of relevant advice and guidance

- **CFE** has several recommendations for optimising nutrient management including soil testing regularly to optimise fertiliser use; matching fertiliser type to soil type to increase N use efficiency and minimise NH_3 emissions; taking a wider approach to crop nutrition than NPK.
- The **COGAP** (Defra, 2009) provides advice on lime and manufactured fertiliser application.
- Guidance for farmers and growers on mineral fertiliser use on different crops is given in **RB209** (AHDB, 2019).
- The **Code of Good Agricultural Practice for Reducing Ammonia Emissions** contains guidance on applying mineral fertilisers effectively and efficiently.

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Table 6. Table of SSM measures currently used or with potential for use in the UK: measures related to soil Inputs (G: Grass; A: Arable; H: Horticulture)

SSM measure	Relevance (G/A/H))	Main threat(s) Addressed	Benefits	Risks/issues	Context/comments
Apply livestock manure (slurry, FYM and poultry)	G/A/H	Loss of SOM Nutrient cycling	• Source of OM* • Source of nutrients (N,P,K); reduced mineral fertiliser use • Supplies trace elements • Improves soil physical, chemical and biological quality	• Nutrient losses to air/water • P build up in soil • Soil contamination • Soil damage during spreading	Following relevant regulations and guidelines for timing/amount/method of application will minimise risks
Apply compost/digestate					
Apply biosolids					
Return straw/crop residues	A/H			• Short term N immobilisation	
Apply lime	G/A/H	Acidification	• Optimises soil pH • Can improve soil structure, nutrient cycling & biodiversity • Reduces PTE availability • Reduces Al toxicity	• Can affect availability of trace elements • May alter microbial OM decomposition rate	Guidance on use of lime is provided in RB209
Apply gypsum	G/A/H	Compaction Nutrient cycling	• Improves soil structure (saline soils only) • Source of sulphur	• Soil contamination (recycled waste gypsum) • Has little effect on soil pH	Follow relevant regulations/guidelines to minimise risks from recycled waste gypsum
Apply (organic material) mulch	A/H	Erosion Loss of SOM Nutrient cycling	• Protects soil from erosion • Source of OM* • Source of nutrients (N,P,K); reduced mineral fertiliser use		Mulching with plastic will protect against erosion, but will not supply SOM and can lead to pollution.
Optimise timing/amount/ method of OM applications**	G/A/H	Nutrient cycling Compaction Erosion	Reduced risk of: • Nutrient losses to air/water • P build up in soil • Soil contamination • Soil damage during spreading	• Can be difficult to achieve for some soil types and climatic conditions • Risks can never be eliminated	Follow relevant Regulations and Best Practice Guidelines
Optimise irrigation practices	A/H	Salinisation	Reduced risk of: • Soil salinisation		Irrigation is soil type/region/crop specific. Threat may increase in future.
Optimise agrochemical use***	G/A/H	Biodiversity loss	Reduced risk of: • Biodiversity loss • Soil compaction (less trafficking)	• Need to balance reducing soil risks with maintaining farm productivity	
Optimise mineral fertiliser use	G/A/H	Nutrient cycling	Reduced risk of: • Nutrient losses to air/water • P build up in soil • Soil contamination • Soil compaction (less trafficking)		See RB209 for guidance on mineral fertiliser use for different crops. Abide by EU Fertiliser Regulation to minimise soil contamination risks.

*Inputs of organic materials will directly address the threat of 'loss of SOM', but the added OM will also improve soil structure and hence also reduce the risk of erosion and compaction.**Including use of N inhibitors; manure incorporation; precision slurry spreaders ***Including: integrated pest management; no broad-spectrum herbicides; pathogenic antagonists; coated seeds

5.2. SSM measures relating to grass and grazing management

5.2.1. Extensive grazing.

Brief evidence review

Extensive grazing can be defined as large-scale, low-input grazing systems which can enhance or maintain the biodiversity of grasslands (and reduce the risk of erosion and compaction). Low input systems tend to have lower grazing intensities which will affect soil physical structure and ability to store soil carbon (C), as well as influencing soil nutrient cycling (See Section 5.2.4). Extensive grazing was included by EEIG Alliance Environnement (2020) as a practice contributing to improved soil quality (Figure 6). There is good evidence that extensive grazing is an important factor contributing towards above-ground biodiversity in UK grasslands. For example, Tallowin *et al*. (2007) reviewed UK studies addressing some of the impacts of grazing management on both species-rich and species-poor lowland neutral grassland. The review found that for species-rich grassland, less intensive grazing pressure maintained botanical diversity and the abundance of positive indicator species of nature conservation value over a 5-year period and also enhanced faunal diversity and abundance.

There is less evidence that reduced grazing intensity is beneficial for soils, although N inputs will be lower because there will be fewer animals compared with intensive grazing systems. De Vries *et al* (2012) reported that extensive grazing management promotes plant and microbial N retention and lower N leaching losses in temperate grasslands, due to a greater immobilisation of N by a more fungal-dominated microbial community. Evidence from the UK is limited, although Smith *et al*. (2015) cited two long-term experiments (at one drier and one wetter grassland site in Scotland) undertaken by Marriott *et al*. (2010), which compared the impacts of extensive grazing, abandonment and continued intensive grazing on soil parameters, and found that on the drier site extensive grazing resulted in a build-up of soil C. Ward *et al*. (2016) found that C concentrations in soil decreased as management intensity increased, but greatest soil C stocks (accounting for bulk density differences), were at intermediate levels of management. A recent global review and meta-analysis of the impacts of grazing intensity on SOC storage and other soil quality indicators in extensively managed grasslands (Abdalla *et al*., 2018) found that the impact of grazing intensity on SOC is climate dependent. These authors also found that increasing grazing intensity increases soil total N and bulk density, but has no effect on soil pH. In Scotland, Skiba *et al* (2013) measured GHG (CO_2 and N_2O) fluxes from a semi-natural, extensively sheep-grazed drained moorland and intensively sheep-grazed fertilised grassland and found that the 4-year average GHG budget for the grazed grassland was approximately 4 times higher than for the moorland, reflecting the higher N inputs in the intensively grazed system.

Summary of relevant legislation and government schemes (England)

- **SFI**: LIG1 and LIG2 relate to managing grassland with very low inputs and aim to protect the soil from erosion, whilst keeping soils healthy and carbon-rich.

Summary of voluntary schemes, initiatives and advice (England)

- None identified.

5.2.2. Rotational grazing or similar.

Brief evidence review

Alternative grazing practices characterised by short, intensive grazing events with long rest/recovery periods (e.g. mob, holistic, strip, long grass, voisin, paddock, cell, techno etc) are claimed to have many benefits including increasing sward productivity, reducing the need for fertiliser inputs, increasing SOM and enhancing biodiversity. Possible negative impacts include reduced sward digestibility and increased risk of soil damage from livestock poaching. Whilst this type of grazing was not identified as an SSM practice in the literature review, it is commonly recognised as a core regenerative agriculture activity (Giller *et al*., 2021), and has been included here due to the current level of interest and claims made about benefits to soils. A recent review for Defra (Dowers *et al*., 2023) found only limited field experimental evidence to support the assertion that mob/holistic grazing increases SOM and reported limitations with the methodology of some of the studies. The review also found very few studies which had measured the impacts of these grazing practices on soil nutrient supply or fertility, whilst the experimental evidence on the impacts on soil physical properties was inconclusive. A previous review of grassland management and soil C also concluded that the evidence that rotational grazing increases soil C stocks was inconclusive (Conant *et al*., 2017). Anecdotal evidence for soil benefits can be found in a British study conducted in 2019 where Wagner *et al* (2023) surveyed 15 farms in England and Scotland run by members of the Pasture-Fed Livestock Association (PFLA). Benefits to soil and ecosystem health were mentioned by the majority of interviewed farmers, who specifically alluded to aspects of soil fertility, soil C, water infiltration capacity, and soil biodiversity.

Summary of relevant legislation and government schemes (England)

- **SFI**: LIG1 and LIG2 relate to managing grassland with very low inputs and aim to protect the soil from erosion, whilst keeping soils healthy and carbon-rich.

Summary of voluntary schemes and initiatives (England)

- **Regenagri** standards for regenerative livestock management include rotational grazing as a method to optimise pasture fertility, increase soil health and SOM, and optimise use of on-farm resources.

5.2.3. Manage grazing season length; Reduce stocking density; Reduce/exclude grazing in vulnerable areas/times; Move feed/water troughs regularly.

Brief evidence review

Reducing stocking density, reducing or excluding grazing in vulnerable areas and moving feed/water troughs regularly were all proposed as best practice measures for managing SOM in agriculture by Bhogal *et al*. (2009) based largely on evidence from the 'Inventory of Methods to Control Diffuse Water Pollution from Agriculture' (Cuttle *et al*., 2007). Reduced stocking density was also identified by Tepes *et al*. (2021) as a sustainable land management practice. Collins *et al.* (2018) included 'reducing field stocking rates when soils are wet' together with 'reducing the length of the grazing day/grazing season' as industry supported measures for reducing diffuse agricultural pollution.

Reducing stocking density helps to minimise soil structural damage from poaching and hence reduce soil/nutrient/SOM losses. Livestock, particularly cattle, can cause severe damage to river/stream banks when accessing drinking water. The vegetative cover is destroyed and the soil badly poached, leading to bank erosion and increased transport of soil particles and associated nutrients into the watercourse. Fencing to prevent access eliminates this source of erosion and SOM loss, as well as associated waterway pollution. Regular movement of feed/water troughs when the soil is wet can reduce damage to the soil and improve the distribution of excreta. Managing grazing season length according to the soil/weather conditions will also reduce the risk of soil damage, by ensuring that livestock are not grazed on wet soils that are vulnerable to damage by compaction and erosion.

Summary of relevant legislation and government schemes (England)

- The **Nitrate Pollution Prevention Regulations** (SI, 2015;2016) place limits on the maximum stocking rates in NVZs based on the amount of livestock excreta N produced (i.e. 170 kg N/ha), although this is a farm level limit rather than a field limit.
- Some **Countryside Stewardship** agreements may include stocking density requirements and prescribed grazing periods.

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** requires that in organic agricultural systems, stocking density is low enough to prevent poaching, over-grazing, application of more than 170 kg N/ha/year, and pollution.
- **Regenagri** standards for regenerative livestock management include grazing density management to avoid overgrazing and maximise recovery time for grasslands and avoiding grazing during wet winter months, preventing soil poaching and compaction.
- **Pasture for Life** requires that the number of livestock on a holding does not compromise the soil condition, the productivity of the pasture or the welfare of the animals.
- **LEAF Marque** requires that measures are taken to avoid damage to grassland by livestock and to optimise biodiversity, including adjusting stocking rates, adjusting animal movements and/or using rotation, positioning of gateways, fencing, supplementary feeders and drinkers.
- **Biodynamic Certification** limits the total number of livestock kept to a maximum of 2 livestock units (LU) per ha and states that the stocking density must also be low enough to avoid poaching, over grazing, and pollution of water courses (in most cases a sustainable stocking rate would typically be lower than 2 LU/ha.)

Examples of relevant advice and guidance

- **CFE** include the following recommendations related to grazing management:
  - Only outwinter livestock on grassland where damage risk is low.
  - Consider where livestock are fed overwinter to avoid poaching or compaction.
  - Minimise compaction – consider where troughs, feeders and gates are located.
  - Minimise compaction - by careful management of stocking rate.
- The **COGAP** (Defra, 2009) gives advice for the control of poaching of soil by livestock and avoiding runoff, including removing stock when soils are too wet and moving supplementary feeders. It also advises against exceeding the livestock carrying capacity of the land by accounting for feed, soil, climate and infrastructure.
- Various measures for reducing poaching (e.g. reducing stocking rates, moving troughs and feeders) are recommended in the **AHDB Beef and Sheep Manual 3** (Improving soils for Better Returns).

5.2.4. Multi species/diverse swards (including legumes and deep rooting species).

Brief evidence review

Using multi species or diverse swards was not mentioned specifically in the literature reviewed as an SSM measure. However, introducing legume species (e.g. red/white clover, vetch, bird's-foot trefoil, sainfoin) and forbs (e.g. ribwort plantain, chicory) into swards has received much recent research attention, with the topic recently reviewed as part of Defra's 'Improved Forages' project (Nicholson *et al.*, 2024). Recent interest in the use of multi-species (MS) swards has been driven by aspirations to increase the quality of pastures and reduce the seasonality of herbage supply, whilst realising environmental and ecological benefits. Several detailed reviews and meta-analyses have been published identifying many studies where beneficial effects of MS swards on environmental metrics such as soil quality, GHG emissions, C sequestration and biodiversity have been recorded (see Nicholson *et al*., 2024). However, the authors of these review papers also identified many areas where knowledge of the environmental impacts of MS swards is lacking and highlighted the need for longer-term studies and evaluation on commercial farms. Some challenges associated with establishment and persistence have been reported.

Summary of relevant legislation and government schemes (England)

- **SFI**: LIG1 and LIG2 for low input grassland aim to produce a sward with flowering grasses, wildflowers, and variety of plants.
- **SFI:** SAM3 (Herbal leys) aims to "provide varied root structures … to help improve and maintain the soil's structure, carbon, biology and fertility".
- **Countryside Stewardship:** GS4 is for legume and herb-rich swards and GS6 is for management of species -rich grassland

Summary of voluntary schemes and initiatives (England)

- **Regenagri** standards for regenerative livestock management include increasing grassland botanical diversity as a method to increase biodiversity and soil health.
- **Pasture for Life** recommends that deep rooting plants other than brassicas or grass species should be included as part of the species mix.

Examples of relevant advice and guidance

- **CFE** includes increasing sward biodiversity (e.g. variety of grass species, herbs, deep rooting species) as a means to improve soil health.

5.2.5. Regular re-seeding.

Brief evidence review

Although not mentioned as an SSM method in any of the literature reviewed, regular re-seeding of grass swards can maintain effective rooting and productivity by introducing new species (e.g. clover) and more efficient/resilient grass varieties. Reseeding can also address soil compaction caused by trampling and trafficking, and may prevent bare patches developing, thereby reducing erosion risks. However, this method should not be used unless the sward is already degraded as unnecessary soil disturbance can lead to erosion and loss of SOM.

There seems to be little evidence on the benefits (or disbenefits) of grassland reseeding for soils. Fornara & Higgins (2022) reviewed the literature and concluded that there was no overall consensus on the effects of grassland tillage and reseeding on long-term soil C stocks, with factors such as the frequency of soil disturbance, ploughing and reseeding method, and soil type all having an important influence. Moreover, they found that relationships between soil tillage frequency and long-term changes in soil bulk density and SOC stocks in grasslands was poorly studied and understood. In their own study, Fornara & Higgins (2022) sampled 500 grassland fields in Northern Ireland which had undergone varying numbers of tillage and reseeding events. Soil C concentrations were largely driven by bulk density (related to the degree of soil compaction): grasslands mainly managed for grazing were significantly less tilled and reseeded and had soils with lower bulk density and higher C concentrations than grasslands managed for silage production. This suggests that while increases in the frequency of tillage and reseeding can negatively affect soil C concentration, the soil C storage potential of agricultural grasslands (calculated as the product of C concentrations and bulk density) can be more affected by increases in soil compaction associated with greater machinery traffic. To determine whether extending the time interval up to 20 years between grassland reseeding could increase stable SOC stocks, Elias *et al.* (2023) surveyed soils from three UK grassland farms on contrasting soil types. Soil C stocks were found to be curvilinearly related to sward age, with rapid initial increases after reseeding. The authors recommended that "*where possible grasslands should be maintained continuously to maximise SOC stocks*". Feigenwinter (2022) and Schils *et al*. (2022) also concluded that reseeding practices should be well-considered and only performed if absolutely necessary.

Summary of relevant legislation and government schemes (England)

- None identified

Summary of voluntary schemes and initiatives (England)

- **Pasture for Life** requires farms to have a pasture management plan including re-seeding/over-seeding targets.

Examples of relevant advice and guidance

- The **COGAP** (Defra, 2009) recommends cultivation and re-seeding as necessary to reestablish green cover.
- **CFE** suggest re-seeding regularly to maintain effective rooting and productivity.

5.2.6. Silvopasture/agroforestry

Brief evidence review

Agroforestry/silvopasture was identified as a regenerative agriculture activity by Giller *et al.* (2021). It is claimed to have many agricultural, ecological and climate benefits including improving soil structure and water storage capacity, capturing nutrients and building SOM. A review of the recent literature from northwest Europe by Nicholson *et a*l (2024) found some evidence of soil benefits in previous reviews of the topic. For example, Dumont *et al*. (2020) commented that trees in silvopastoral systems buffer grasslands from large temperature fluctuations, reduce soil evaporation and increase soil water infiltration, concluding that there are a wide range of conditions where multispecies plant communities can help farmers adapt to climatic events. Another review by Sollen-Norrlin *et al*. (2022) concluded that agroforestry systems can have benefits for C sequestration, nutrient cycling, soil biodiversity and water retention, and can reduce soil erosion. Pantera et al (2021) identified several sources of information, showing that agroforestry can provide climate change mitigation via C sequestration in the subsoil. From their comprehensive review, Jordon *et al*. (2020) concluded that "*it is clear that implementation of agroforestry has the potential to sequester carbon, reduce soil erosion, and, with appropriate management, improve water quantity and quality regulation*".

A recent field-based study (funded by AHDB) of eleven farms in South Powys, measured soil properties on a mix of lowland and upland livestock farms (Staddon *et al*., 2022). Grazing in silvopasture tended to result in fields with high or very high soil C content for some farms but not others, possibly reflecting the length of time since the trees were planted. On some farms the silvopasture fields also had the greatest microbial (bacterial or fungal) taxon richness, although there was no obvious pattern with regard to field management regimes. However, field-based evidence for the benefits to soils (particularly in a UK context) is lacking; this is required to enable informed decision-making by farmers, advisory services and policymakers (Sollen-Norrlin *et al.*, 2022).

Summary of relevant legislation and government schemes (England)

SFI: Options AGF1 and AGF2 relate to establishing and maintaining silvoarable and silvopasture agroforestry systems, so trees can be integrated and managed in arable fields or grazed grassland across different farming systems.

Countryside Stewardship: includes options to create (WD6), restore (WD5) and manage (WD4) lowland woodland and parkland; and to create (WD12), restore (WD11) and manage (WD10) upland woodland and parkland

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** includes rules for managing livestock which have access to woodland or forest areas.
- **Regenagri** includes agroforestry as an example of a beneficial perennial cropping system which can improve water and nutrient dynamics, soil structure and biodiversity.

Table 7. Table of SSM measures currently used or with potential for use in the UK: measures related to grass and grazing management. (G: Grass; A: Arable; H: Horticulture)

SSM measure	Relevance (G/A/H))	Main threat(s) Addressed	Benefits	Risks/issues	Context/comments
Extensive grazing*	G	Biodiversity loss	• Maintains or enhances biodiversity. • Increases C storage. • Influences nutrient (N) cycling. • Improves soil structure.	• Benefits for SOC storage may be climate dependent	
Rotational grazing or similar**	G	Loss of SOM Nutrient cycling Biodiversity loss	• Enhances biodiversity. • Increases C storage. • Reduces need for mineral fertiliser	• Soil damage from poaching	Limited evidence for benefits to soils
Manage grazing season length (based on soil/weather conditions)	G	Compaction Erosion	Reduces risk of: • Soil compaction and erosion • Diffuse water pollution		
Reduce stocking density	G				
Reduce/exclude grazing in vulnerable areas and times***	G				
Move feed/water troughs regularly	G				
Multi species/diverse swards****	G	Biodiversity loss SOM loss Nutrient cycling	• Enhances biodiversity • Improves soil structure • Reduces need for mineral fertilisers • Increases C storage • May reduce GHG emissions	• May not be appropriate on established swards.	
Regular re-seeding	G	Compaction	• Can relieve soil compaction • May reduce risks of bare patches and erosion	• Can lead to (short-term) SOM loss • Only beneficial for soil if the sward is already degraded.	
Silvopasture/agroforestry	G	Loss of SOM Nutrient cycling Biodiversity loss	• Enhances biodiversity. • Increases C storage. • Influences nutrient cycling • Improves soil structure.		Limited evidence from the UK

*Defined as large-scale low input grazing systems

**Grazing practices characterised by short, intensive grazing events with long rest/recovery periods Including: mob, holistic, strip, long grass, voisin, paddock, cell, techno grazing etc

***Including fencing off watercourses from livestock

****Including greater use of legumes and deep rooting species

5.3. SSM measures relating to crops and rotations

5.3.1. Autumn established cover crops/green manures.

Brief evidence review

Cover crops are mentioned as a SSM measure by numerous UK and non-UK sources (see Section 4). Many years of research and an extensive evidence base have shown that using cover crops and green manure over bare ground in winter can help to reduce soil erosion and runoff; retain nutrients in the soil; and increase SOM content and the numbers of beneficial soil microbes and earthworms (see, for example, the review of cover crop benefits by White *et al.,* 2016 and the AHDB-funded 'Maxi Cover Crop' project by Bhogal *et al*., 2020). Some useful examples of how cover crops have been used in practice for SSM as part of the Sustainable Intensification Research Platform (SIP) in the UK can be found in SIP (2018; https://www.siplatform.org.uk/), and a farmer-led guide for cover cropping has recently been released (https://www.covercropsguide.co.uk). In a rapid evidence assessment of the use of vigorous rooting green crops to rectify soil structural damage, Berdeni *et al*. (2021) found limited evidence of a clear and consistent effect of cover crops and green manures on soil structure. Some evidence suggests that when integrated into reduced or no till cropping systems for multiple years, cover crops can be of benefit to topsoil structure. However, there is a lack of longer terms studies (> 1.5 years) and studies which quantify changes to soil structure at depths > 30 cm. There is some evidence that tap-rooted species are most suited to improving soil structure in compacted soils, however more evidence is needed to determine which species and species mixtures perform best, the levels and depths of soil compaction that can be remediated and the timescales for these changes.

Recently, Chaplot & Smith (2023) questioned the idea that cover crops are an effective method for increasing SOC stocks. However, this has in turn been challenged by Poeplau *et al.* (2024) who referenced several recent reviews and meta-analyses on the subject that have shown positive effects of cover crops on SOC (e.g. Qin *et al*., 2023, Beillouin *et al*, 2023).

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that land managers must ensure that reasonable precautions are taken to prevent agricultural diffuse pollution resulting from land management and cultivation practices on agricultural land, including undersowing or sowing a cover crop to stabilise soil after harvest.
- **SFI**: SAM2 (Multi-species winter cover) aims to protect the soil surface and provide root growth that benefits soil structure, supports soil biology and minimises nutrient leaching, soil erosion and runoff.
- **Countryside Stewardship:** SW6 is for winter cover crops.

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** requires organic farmers to identify areas prone to run off and soil erosion, and adopt appropriate strategies to minimise these; the strategies include overwinter green covers. They also state that plants must be nourished primarily through the soil ecosystem including by using green manure crops.
- **Regenagri** includes cover cropping as a method for regenerative crop production.
- **Fair to Nature** requires that at least 10% of the farmed area is managed to provide a range of wildlife habitats and features; this can include winter cover crops.

- **Biodynamic certification** recommends using balanced rotations including green manures and companion planting to break pest and disease cycles and provide crop diversity.

Examples of relevant advice and guidance

- **RB209** (AHDB, 2019) provides advice on integrated plant nutrient management, including cover cropping.
- The **COGAP** (Defra, 2009) recommends taking positive action to maintain or increase SOM to improve soil stability and increase workability; methods include introducing green manures into the rotation.
- **CFE** recommend the use of cover cropping to improve soil structure and manage pests.
- Information on cover crops is also provided by **AHDB** on their website (https://ahdb.org.uk/cover-crops).

5.3.2. Overwinter stubble.

Brief evidence review

Overwintered stubble is listed in some UK sources as a SSM method to reduce runoff and erosion, and retain nutrients in the soil, although the main reason for including this measure in agri-environment schemes is to provide food and shelter for wildlife. There is a strong peer-reviewed evidence base on the benefits of overwinter stubble for birds and farmland wildlife; a good summary of this can be found in Dicks *et al.* (2020). There are less data on the benefits overwinter stubble provide for soils; indeed an evidence review by Chapman *et al*. (2018) concluded that "stubble retention in arable fields has no consistent impact on soil organic carbon storage and earthworm population, but the evidence for this is based on a limited number of studies……Very few studies compared the soil health of arable fields with and without stubble retention. However, it could be considered a type of cover crop as it protects the soil from erosion during the winter" (https://committees.parliament.uk/writtenevidence/95915/html/). This is supported by a study of 85 sites in the South Downs National Park (Boardman *et al*., 2017) which found that switching from winter cereals to overwinter stubble reduced the risk of soil erosion at sites of former serious erosion. Elsewhere, studies have shown that stubbles can be effective in preventing soil erosion by wind (e.g. Cong *et al.,* 2016; Liu *et al*, 2018). However, bare maize stubble (that often leaves the soil compacted following harvest in autumn) should not be left over winter because of the high risk of soil erosion (see, for example, Jaafar & Walling, 2010; Palmer & Smith, 2013), nutrient and sediment losses to watercourses and the reduction in soil biological activity (Maize Growers Association; CFE https://www.cfeonline.org.uk/environmental-management/manage-maize-to-avoid-soil-erosion/).

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that reasonable precautions should be taken to prevent significant soil erosion and runoff from land management and cultivation practices (such as seedbeds, tramlines, rows, beds, stubbles (including harvested land with haulm), polytunnels and irrigation).
- **Countryside Stewardship:** OP1, AB2 and AB6 are for overwintered stubble.

Summary of voluntary schemes and initiatives (England)

- **Fair to Nature** requires that at least 10% of the farmed area is managed to provide a range of wildlife habitats and features; this can include overwintered stubbles.

Examples of relevant advice and guidance

- The **COGAP** (Defra, 2009) recommends that where it is not practical to establish a cover or catch crop, uncultivated stubble should be left for as long as possible. In addition, it recommends that land should be left in stubble (or roughly cultivated) over winter to minimise run-off and erosion before spring sown crops.
- Information on leaving stubble over winter is available on the **Defra** website (https://defrafarming.blog.gov.uk/leave-stubbles-over-winter/) .

5.3.3. Early establishment of winter crops.

Brief evidence review

Early sown winter crops offer many of the same benefits for soils as cover crops or green manures (see Section 5.3.1). Establishing autumn-sown crops early (by mid-September) will result in more established vegetation cover to protect the soil from the erosive impacts of rainfall over winter (Bhogal *et al*., 2009); in addition an early sown crop will take up some available N from the soil whilst it establishes, reducing the risk of over winter nitrate leaching.

A recent publication by Boardman & Favis-Mortlock (2023) reported outputs of a conceptual model to assess the effectiveness of early establishment of autumn-planted cereals for reducing soil erosion by water. The model, based on the relationship between drilling date, date of attainment of a sufficiently protective crop cover and the timing of rainfall, found that the crucial factor was the timing of autumn and early winter rainfall. Since this cannot be predicted or controlled, the authors asserted that erosion control advice to farmers, which is based on choice of date of drilling to minimize erosion during the 'window of opportunity', is both difficult to formulate and likely to be ineffective. They concluded that "sites at risk of erosion need to have better thought-out mitigation measures in place, rather than relying on a fortuitous temporal pattern of autumn and winter rainfall to minimize the risk of erosion".

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that land managers must ensure that reasonable precautions are taken to prevent agricultural diffuse pollution resulting from land management and cultivation practices on agricultural land, including establishing crops early in autumn months, and during dry conditions.

Summary of voluntary schemes and initiatives (England)

- **Fair to Nature** recommend that 10% of farmed areas are used for wildlife habitats (e.g. winter crops).

5.3.4. Diverse rotations

Brief evidence review

Diverse crop rotations are a key component of regenerative agriculture systems (Magistrali *et al.,* 2022). Diversifying crop rotations is beneficial for biodiversity and including more legumes in the rotation will help to fix N from the atmosphere and reduce the need for N fertiliser applications to meet optimum crop demand. Legume-based rotations can also provide advantages in terms of main crop yields (Zhao *et al.,* 2022). Nemecek *et al*. (2008) found that per unit of cultivated area, the introduction of grain legumes into intensive cereal crop rotations led to reduced energy consumption due to reduced application of mineral N-fertilisers (no N to the grain legume and less N to the following crop) and more opportunities for using reduced tillage techniques. Greater diversification of the crop rotation also decreased weed and pathogen problems thereby reducing the need for pesticides. Legumes have been found to release 5–7 times less GHG per unit area compared with other crops and can promote carbon sequestration in soils as outlined in a review by Stagnari *et al*. (2017). A field-based study at sites in Germany and Sweden which tested cropping systems with and without legumes found that in both case studies, cropping systems with legumes reduced N_2O emissions with comparable or slightly lower nitrate-N leaching (Reckling *et al,* 2016). In contrast, Nemecek *et al*. (2008) found that nitrate leaching was generally higher from legumes, but could be reduced by including catch crops or by early sowing of winter grain legumes; no differences to soil quality and biodiversity were found.

Various authors have reported that using deep rooting crops and breeding crop plants with deeper and more bushy root systems can have many benefits for soils. Including plants with deep, strong taproots in the rotation can help to avoid, delay or alleviate soil compaction, improving water infiltration, gas exchange and loosening the soil structure for following crops (e.g. Hamza & Anderson, 2005; Piccoli *et al,* 2022). A review by Kell (2011) outlined how plants with more extensive root systems can improve carbon, water and nutrient sequestration in soils, thus providing resistance to drought, flooding and other consequences of climate change, as well as reducing nutrient runoff (see also Section 5.2.4).

Summary of relevant legislation and government schemes (England)

- A crop diversification requirement known as 'the three crop rule' was part of Common Agricultural Policy (CAP) cross compliance rules, and was discontinued in 2021 following a derogation in 2020 due to extreme weather conditions (i.e. flooding).

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** state that in organic systems plants must be nourished primarily through the soil ecosystem including by using a varied crop rotation and/or legumes.
- **Regenagri** includes implementing a rotation of 2 or more crops including at least one legume. Farms must implement a broad crop rotation across at least 75% of their agricultural land.
- **LEAF Marque** requires a long-term cropping plan wherein the rotation/cycle is sustainable and appropriate to the farm business, including the soil, livestock (where applicable) and climate.
- **Biodynamic certification** recommends the creation of a diverse ecosystem within and around the crop to encourage natural predators by choosing crops and varieties that are well adapted to the environment including the use of resistant varieties, and using balanced rotations including green manures and companion planting to break pest and disease cycles and provide crop diversity.

Examples of relevant advice and guidance

- **CFE** suggest using at least a 3-crop rotation, maximising cropping diversity (extending the rotation) and introducing legumes into the rotation.

5.3.5. Leys/rotational grass.

Brief evidence review

Using leys in arable rotations has been proposed as a SSM measure by numerous UK and non-UK sources (see Section 4). A recent French review of the benefits of ley pastures in cropping systems concluded that they provide or enhance a large set of ecosystem services including soil conservation, nutrient provision and recycling, soil water retention, biological pest control, water purification, climate regulation, habitat provision and forage production, as long as their use is well-managed (Martin *et al*., 2020). Jarvis *et al*. (2017) found that higher proportions of ley in the rotation (length of ley varied from 1 to 5 years in a 6-year rotation), improved topsoil SOC, earthworm numbers and soil structure (porosity and bulk density) at a long-term experimental site in Sweden.

In the UK, Ball *et al*. (2005) found that conversion to ley-arable cultivation can provide benefits resulting from reduced soil disturbance, larger litter inputs and permanent vegetative cover/presence of roots. Johnston *et al*. (2017) reported that topsoil SOM increased by 0.25% over a 30-year period following the introduction of a 3-year grass ley in a 5-year rotation (at the Woburn ley arable experiment). Zani *et al.* (2020) found that grazed temporary grass-clover leys in crop rotations can have a positive impact on soil quality (pH; extractable P, K, bulk density, aggregate stability, total C, microbial biomass C) under both conventional and organic agricultural systems: In a project looking at sustainable beef systems on arable units, Sagoo *et al*. (2022) also measured increases in SOM and earthworm numbers from 3 years of a grass clover ley. Herbal leys (mixtures of legume, herb and grass species) have particular benefits for soils including improved structure and drainage (from the use of deep rooting species), increased N fixation with higher legume content (and hence reduced fertiliser costs), increased soil C sequestration and increased earthworm numbers. However, success can vary and it is important to choose species mixes to suit the soil type and manage grazing/cutting appropriately. A recent review paper led by authors from Bangor University (Cooledge *et al*., 2022) looked at the potential agronomic and environmental benefits of reintroducing herb- and legume-rich multi species leys into arable rotations. The literature reviewed (from Europe and elsewhere in the world) indicated that use of ungrazed leys in arable-ley rotations can increase C sequestration, symbiotic N fixation, water infiltration, and biodiversity of soil fauna and microbial communities. However, most research had been conducted on grass or grass-clover leys, so the evidence base to support the use of multi species leys is limited. A key message was that, due to their complexity and complementarity of species, MS leys can potentially deliver greater ecosystem services than grass or grass-clover leys. Increasing species diversity by using a four to eight-species ley can offer greater multifunctionality and opportunities to improve soil quality than a monoculture grass or lower diversity grass-clover ley.

According to the ADAS-led Defra and AHDB-funded ‘Grass and Herbal Leys Farm Network’ project more research on the impact of temporary leys on soil quality is needed (Sagoo *et al*., 2018b), a requirement reiterated by Martin *et al* (2020) who called for interdisciplinary research involving soil scientists, agronomists, geneticists, and ecologists to improve our understanding of the role of ley pastures in cropping systems.

Summary of relevant legislation and government schemes (England)

- **SFI**: SAM3 (Herbal leys) aims to provide varied root structures to help improve and maintain the soil’s structure, carbon, biology and fertility.
- **Countryside Stewardship:** OP4 is for multi-species leys

Summary of voluntary schemes and initiatives (England)

- **Fair to Nature** requires that at least 10% of the farmed area is managed to provide a range of wildlife habitats and features; this can include herb-rich/clover leys.

Examples of relevant advice and guidance

- **CFE** suggest introducing (diverse) leys into the rotation.
- The **COGAP** (Defra, 2009) recommends taking positive action to maintain or increase SOM to improve soil stability and increase workability; methods include introducing grass into the rotation.
- Advice on establishing and managing grass, grass/clover and leys and herbal leys is provided on the **Defra** and **AHDB** websites.
- **RB209** (AHDB, 2019) provides advice on integrated plant nutrient management, including grass leys.

5.3.6. Vegetated Fallow.

Brief evidence review

Although not identified in the literature as an SSM, establishing a vegetated fallow (rather than bare soil) can help restore natural nutrient balances and control weeds, pests and diseases.

A global review of vegetated fallow effects on soils (Nielson & Calderon, 2011) concluded that systems that reduce or limit bare fallow frequency and tillage intensity generally result in greater amounts of surface crop residues. Those residue increases generally produce positive effects on soil quality for crop production, including increases in soil OM, nutrients, physical structure, water content, and microorganisms, as well as reductions in soil loss by wind and water erosion. In a more recent review, Abhiram & Eeswaran (2022) found that the major benefits of legumes in a summer fallow are N enrichment, improved soil moisture retention, crop yield improvement, and enhancement of soil health as a result of improved physical properties and erosion control. They also identified several factors which might limit the wider adoption of legumes into the summer fallow including increased environmental N losses (via nitrate leaching and N_2O emissions) and depletion of soil water and phosphorus. Importantly, most of the evidence from both of these reviews is from non-UK studies and may not be applicable to UK agroclimatic conditions.

Summary of relevant legislation and government schemes (England)

- **SFI**: NUM3 (legume fallow) aims to produce areas of flowering plants from late spring and during the summer months, and to manage nutrient efficiency and improve soil health.
- **Countryside Stewardship:** AB15 is for la two-year sown legume fallow.

Summary of voluntary schemes and initiatives (England)

- **Certified Regenerative** states that land used for production must not be left bare for more than 4 weeks. The only exception is if it has been justified in the regenerative plan.

Examples of relevant advice and guidance

- Advice on creating a 2-year sown legume fallow is provided on the **Defra** website. (https://defrafarming.blog.gov.uk/create-2-year-sown-legume-fallow/).

5.3.7. Intercropping/companion crops.

Brief evidence review

Intercropping refers to the practice of growing two or more crops in close enough proximity to allow biological interaction. Similarly, companion cropping simply refers to growing two or more crops together. The use of intercropping was suggested as a key soil protection practice by Tepes *et al*. (2021).

Whilst there have been many reviews published of the benefits of intercropping on agricultural productivity and environmental sustainability, few of these have focused on soil and very few are from UK based authors. An exception is the synthesis of research on the agronomy, plant physiology and ecology of intercropping by Brooker *et al.* (2015). These authors commented that in temperate regions the benefits of intercropping depend on a range of factors including the crop species being grown, the sowing ratio and the specific growing conditions. When benefits do occur, they are a result of the more complete exploitation of resources (e.g. solar radiation, water, soil and fertilisers) from beneficial neighbour interactions and in some cases from continuous soil cover. A Nuffield Farming Scholarships Trust report on the potential for companion cropping and intercropping on UK arable farms (Howard, 2016) found that these practices had numerous benefits for soils, crop protection and the environment, including reduced risk of nitrate leaching, increased N fixation by leguminous crops (and slow N release during senescence), more efficient nutrient use (due to different rooting depths and patterns), increased SOM and reduced soil water loss. In the EU, an ongoing project (LEGUMINOSE) aims to establish intercropping as a climate-smart farming practice and includes a work package on soil fertility; this project will end in 2026 and may yield some useful results (https://www.leguminose.eu/). Some trials of intercropping/companion cropping have been undertaken on UK monitor farms, and farmer knowledge exchange events on using cover crops and companion cropping to build soil health have been organised (see AHDB website for details).

Summary of relevant legislation and government schemes (England)

- **SFI**: IPM3 refers to sowing a companion crop to form a living mulch beneath an arable or horticultural crop to provide multiple benefits, including protecting the soil and improving its condition.

Summary of voluntary schemes and initiatives (England)

- **Regenagri** includes multi-cropping and intercropping as practices which have positive effects on nutrient cycling capacity, pest resistance and weed suppression, ultimately resulting in higher yields and soil health compared to monocultures.
- The **Soil Association** requires organic farmers to identify areas prone to run off and soil erosion, and adopt appropriate strategies to minimise these; the strategies include inter-cropping.
- **Biodynamic certification** recommends using balanced rotations including green manures and companion planting to break pest and disease cycles and provide crop diversity.

5.3.8. Under-sowing

Brief evidence review

Under sowing crops (sometimes referred to as a 'living mulch') is a traditional form of companion cropping where the main cash crop is sown and then clover or grasses are spread over the top, so that the following ley will be ready as soon as the crop has been harvested. A living mulch, such as clover, may be under sown to provide nutrients to the crop (e.g. clover can fix N which can be utilised by the main crop) and is not always intended for use as a ley afterwards. Under sowing helps to maximise ground cover increasing soil health, reducing losses from run off and erosion, suppressing the growth of weeds and regulating temperature at the soil surface. See Sections 5.3.1 and 5.3.7 for more detail on potential benefits of cover crops and companion crops, respectively. A report on UK field trials assessing the impacts of living mulches on cash crop yields and weed composition is also available; this found several potential soil health benefits; significantly increased available N and earthworm counts, and a trend for increased microbial activity and SOM (Lowth, 2023).

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that land managers must ensure that reasonable precautions are taken to prevent agricultural diffuse pollution resulting from land management and cultivation practices on agricultural land, including undersowing or sowing a cover crop to stabilise soil after harvest.
- **Countryside Stewardship:** OP5 is for undersown cereals.

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** requires farmers to identify areas prone to run off and soil erosion, and adopt appropriate strategies to minimise these; the strategies include under-sowing.

Examples of relevant advice and guidance

- **CFE** suggest that run-off erosion risk can be minimised through direct drilling/strip tillage and/or under-sowing.
- Advice on undersowing clover is provided on the **AHDB** website

5.3.9. Integrated livestock

Brief evidence review

Integration of livestock into the arable rotation is a key component of regenerative agriculture systems (Magistrali *et al*., 2022). Integrating (ruminant) livestock into arable rotations requires the establishment of grass or herbal leys to provide suitable grazing or forage for the animals (see Section 5.3.5). The livestock themselves will supply OM and nutrients (NPK) to the soil in their deposited excreta with resulting benefits to soils (See Section 5.1.1). However, not all arable soils are suitable for livestock grazing in winter. To minimise the risk of soil poaching and run-off, fields with sandy soils, good soil drainage and gentle slopes are preferable to poorly drained, heavy clays soils or steep slopes. In all cases grazing must be carefully managed to avoid soil damage from compaction and to minimise diffuse pollution losses. Limited research evidence from the UK was located, although Watson *et al.* (2019) discussed how integrating livestock could improve N and P cycling in European agriculture via improved manure management and crop diversification, including leys, and Sagoo *et al.* (2022) investigated the benefits and challenges of introducing sustainable beef systems on arable units (see Section 5.3.5). A BBSRC-funded project (https://gtr.ukri.org/projects?ref=BB%2FR021716%2F1) is also researching how soil quality might be restored through re-integration of leys and sheep into arable rotations, with an initial overview of the topic published by Schut *et al*. (2021).

According to the AHDB, outdoor pig production systems can work well in an arable rotation and increase soil health, structure and fertility, although we were not able to find any evidence to support this claim. A recent UK study (Sun *et al*., 2022) which looked at soil carbon and nutrient variations in an arable-ley rotation with organic pig production found that the pigs caused significant physical damage leading to soil disaggregation, although the soil structure recovered over the following 2 years. In the UK context outdoor pigs have also been associated with an increased risk of soil erosion and runoff (Evans, 2017). Elevated nitrate leaching losses have also been recorded (Williams *et al.*, 2006a,b), although according to a review by Webb *et al* (2014) changes in outdoor pigs feeding and management have resulted in reductions in N leaching losses of up to 50% less than previously reported. Sun *et al.* (2022) also reported high concentrations of inorganic N at 'hot-spots' around feeders and housings, and the poor soil structure caused by the pigs represented a significant risk of nutrient and soil loss. Research on outdoor pig systems is continuing. A recent study by the University of Leeds used a combined experimental and modelling approach to understand the impact of outdoor pigs on soil C and nutrient dynamics (Pun *et al*., 2024). Whilst soil nutrients, especially P and plant-available N, increased following the introduction of pigs into arable rotations, there was no observed effect on soil pH, bulk density or SOC. Model results indicated that current practices (e.g. 2 years of outdoor pigs and 4 years of arable rotation) could reduce soil C stocks in the long term under a range of climate change scenarios. However, these reductions could be mitigated with sustainable management practices, such as shortening the time when pigs are on the field, reducing the occupancy rates, and introducing grass leys into the rotation.

Summary of relevant legislation and government schemes (England)

- None identified.

Summary of voluntary schemes and initiatives and advice (England)

- **Red Tractor** set standards for outdoor pig welfare and stocking density limits.
- **Pasture for Life** encourages arable producers to integrate livestock into their farm systems.

Examples of relevant advice and guidance

- A **Code of Practice** (for England) sets standards for pig welfare. This specifies that free-draining soils, in low rainfall areas, with lower frost incidence are most suitable for outdoor pigs, and that stocking densities should reflect the suitability of the site and the system of management.
- Advice on introducing and managing livestock in arable rotations is provided by **AHDB** (https://ahdb.org.uk/livestock-and-the-arable-rotation).
- The **National Sheep Association** guide to the Benefits of Sheep in Arable Rotations outlines how sheep can fit into arable rotations and the benefits they can bring to soil structure, soil fertility, weed control, biodiversity and cash flow.
- The **COGAP** (Defra, 2009) provides advice on managing outdoor pigs to protect soils.

5.3.10. Short rotation coppice/biomass crops

Brief evidence review

Growing biomass (or energy) crops such as willow, poplar and miscanthus was identified in several sources as a method for SSM and improving SOM (Bhogal *et al.*, 2009). Woody biomass plantations can reduce water erosion by improving water infiltration, reducing impacts by water droplets, intercepting precipitation and physically stabilizing soil by their roots and leaf litter. However, harvesting of woody biomass may be accompanied by increased erosion (e.g. Kort *et al.,* 1998).

A review for Natural England on the environmental impacts of energy crops (NE, 2009) concluded that despite the release of nitrates at establishment and 'grubbing up' of short rotation coppice, overall nutrient losses from the soil are less than under conventional arable cropping. Because most biomass crop are not ploughed or harvested annually, this benefits the soil structure compared with conventional arable crops, and their lower agrochemical requirement reduces risks from nutrient and pesticide run-off and leaching. However, if non-arable land is converted to biomass crop production, this would lead to losses of soil carbon with implications for soil structure, erosion and GHG emissions. Another UK study (Anejionu & Woods, 2019) used a modelling approach to estimate the 20-year impact of introducing *Miscanthus* on a farm near the Humber Estuary. The study found that careful integration of *Miscanthus* reduces sediment and nutrient loss, and increases biomass yield, without adversely affecting food production. A more recent review by a team of UK and US researchers on the impact of land use change from food (arable and grass) to energy crops (Donnison *et al.* 2021) found an overall positive effect on biodiversity, including increases in soil microbial biomass and arthropod abundance, in addition to improved SOC (see Bhogal *et al*., 2009) and flood mitigation.

Summary of relevant legislation and government schemes (England)

- None identified

Summary of voluntary schemes and initiatives (England)

- **Regenagri** includes biomass perennials as an example of perennial cropping systems that can store greater amounts of carbon (in deep roots and above ground biomass), improve water and nutrient dynamics, improve soil structure, and increase biodiversity.

Examples of relevant advice and guidance

- Guidance on the fertiliser requirements of miscanthus and willow grown as short rotation coppice is given in **RB209** (AHDB, 2019).

5.3.11. Reversion to grassland

Brief evidence review

Arable reversion to permanent grassland was suggested by Bhogal *et al* (2009) as a best practice method for managing SOM. Many studies have investigated how land use changes can impact soil quality, although often these have focussed on the damage to soils caused by cultivating permanent grasslands, urbanisation, soil sealing etc. Indeed, land use change is one of the major threats to soils today (see Smith *et al.,* 2015; Peake *et al*. 2022). Nevertheless, it is possible for arable soils to be converted back into permanent pasture which will have the effect of rebuilding the SOM content and reducing compaction and erosion risks, by providing year-round vegetation cover and reducing damage by trafficking. Permanent reversion to grassland would also offer many of the same benefits to soil quality and biodiversity as the introduction of grass or herbal leys (see Section 5.3.5), although SOM levels would be improved much more than for temporary grassland (e.g. Johnston *et al*. 2009; Conant *et al.*; 2017). Note also the paper by Collier *et al.* (2020) which found significant relationship between 'time since tillage' and SOM and aggregate stability across 14 farms in SW England.

However, some researchers have questioned the assumption that arable reversion will promote carbon storage in soils. For example, Gosling *et al*. (2017) found no differences in SOC stocks (0-30 cm) between grassland up to 17 years old and arable cropland at 14 sites across the UK (because reduced available soil N in grassland resulted in lower productivity and hence lower OM returns). However, soil microbial biomass was higher in the grassland soils and less dominated by bacteria. Other studies have shown that reversion to grassland can reduce the risk of soil erosion (Boardman, 2017) and can lead to a less 'leaky' nitrogen cycle by reducing nitrate leaching and N_2O emissions (e.g. Hu *et al*., 2019) and reduced P losses. Establishing a species rich sward (see Section 5.2.4) will clearly have benefits for both above and below ground biodiversity as demonstrated at a former arable site on a lowland chalky soil in England (Roberts, 2020).

Summary of relevant legislation and government schemes (England)

- **Countryside Stewardship** option SW7 (Arable reversion to grassland with low fertiliser input) states that this option will stabilise soil, reduce nutrient losses, buffer sensitive habitats, and reduce surface runoff and flood risk.

Summary of voluntary schemes and initiatives (England)

- **Regenagri** includes perennial grasslands as an example of perennial cropping systems that can store greater amounts of carbon (in deep roots and above ground biomass), improve water and nutrient dynamics, improve soil structure, and increase biodiversity.

Examples of relevant advice and guidance

- **CFE** suggest converting high risk fields to permanent pasture.
- Information on the benefits of converting arable land to permanent grassland is available on the **Defra** website (https://defrafarming.blog.gov.uk/convert-arable-land-to-permanent-grassland/.)

Table 8. Table of SSM measures currently used or with potential for use in the UK: measures related to crops and rotations. (G: Grass; A: Arable; H: Horticulture)

SSM measure	Relevance (G/A/H))	Main threat(s) addressed	Benefits	Risks/issues	Context/comments
Autumn established cover crops/green manures	A/H	Loss of SOM Erosion Biodiversity	• Reduces risk of soil erosion • Enhances biodiversity • Increase SOM • Retains soil nutrients		
Overwinter stubble	A	Loss of SOM Erosion	• Reduces risk of soil erosion • May enhances biodiversity	• Inconsistent effects on SOM • Maize stubble presents a significant risk of soil erosion	
Early establishment of winter crops	A	Erosion	• Reduces risk of soil erosion • Retains soil nutrients		
Diverse rotations*	A	Biodiversity Nutrient cycling	• Enhances biodiversity • Reduces need for mineral (N) fertiliser • Reduces N losses • Improves soil structure • Increases C storage and water retention		Legumes fix atmospheric N and can reduce mineral fertiliser requirements. Deeper rooting crops can improve soil structure
Leys/rotational grass	A	Loss of SOM Biodiversity Nutrient cycling	• Enhances biodiversity • Reduces need for mineral (N) fertiliser • Can improve soil structure and C storage		Herbal leys can be especially beneficial, although the evidence base is limited
Vegetated Fallow**	A/H	Nutrient cycling Biodiversity Erosion	• Restores nutrient cycles (by fixing N) • Enhances biodiversity • Reduces risk of soil erosion	• Legume fallows may increase N losses, and deplete soil P and SOM	Also used to control weeds and diseases
Intercropping/companion crops	A	Nutrient cycling Biodiversity	• Better exploitation of nutrients and water • Enhances biodiversity		
Under sowing	A	Erosion	• See cover crops and intercropping		
Integrated livestock (livestock in rotations e.g. outdoor pigs)	A	Loss of SOM Nutrient cycling	• Increases supply of nutrients • Increases supply of OM	• Not all soils are suitable • Outdoor pigs can damage soils and cause diffuse pollution	
Short rotation coppice/biomass crops	A	Loss of SOM Erosion	• Increases C storage • Reduces soil erosion risk • Reduces need for agrochemicals	• Can lead to erosion during 'grubbing up' • Can compete with food production	Only willow and miscanthus currently grown commercially in the UK
Reversion to grassland	A/H	Loss of SOM Erosion Nutrient cycling Biodiversity	• Reduces risk of soil erosion • Enhances biodiversity • Increase SOM • Retains soil nutrients	• Can compete with arable and horticultural production	Some research has questioned the C storage potential.

*Including: More legumes/Deeper rooting crops **Not bare soil.

5.4. SSM measures relating to mechanical pressures and cultivation methods

5.4.1. No tillage; Minimum/reduced/strip/conservation tillage

Brief evidence review

Conventional tillage systems which rely on repeated tillage operations (i.e. ploughing) and frequent soil disturbance have been shown to have adverse effects on soil health. No-or zero-tillage (NT) systems in contrast aim to direct drill crops into an undisturbed seedbed, thereby (in theory) reducing any detrimental impact on soils. Similarly, minimum, reduced, strip and other conservation tillage (CT) systems aim to reduce the number of cultivations (or reduce the degree/depth of cultivations) to keep soil disturbance to a minimum. Strip tillage is a modification of direct drilling systems where around one-third of the total field is cultivated. Crop residues are 'removed' from the cultivated strips, with seed drilled direct into the strips. CT has several potential benefits over conventional tillage including conservation of soil moisture, improvements to soil physical properties, reduced risk of soil erosion/sediment loss and diffuse water pollution, and enhancements to biodiversity and wildlife. NT and CT were recommended as SSM methods by several UK and non-UK literature sources.

There is a very large body of work which has investigated the impact of NT on various soil properties and many reviews of the topic. For example, Skaalsveen *et al.* (2019) reviewed recent studies (post-2000) in NW Europe to evaluate the effect of NT on soil functions. They found that NT had great potential as a soil erosion mitigation measure, reducing soil losses and inputs of sediment and particulate P into water bodies. However, NT increased losses of dissolved reactive phosphorus and had little effect on nitrate leaching. Soil structural properties were often worse under NT than CT soils, resulting in decreased water infiltration rates and lower hydraulic conductivity. This was due to topsoil compaction, reduced porosity and high bulk density because there was no topsoil inversion to break up compacted soils. However, several studies showed that soil structure under NT could be improved considerably by introducing cover crops (see Section 5.3.1), but the root and canopy characteristics of the cover crop need to be carefully considered to achieve the desired effect. Another review (Blanco-Canqui & Ruis, 2018) concluded that NT generally improved soil physical properties, although these effects were largely confined to the top 10 cm. Cover crops or OM additions (see Sections 5.1.1 and 5.3.1) were reported to enhance NT performance but the success (or otherwise) of NT systems is strongly dependent on soil texture and climatic conditions. A similarly large body of evidence exists for the effects of various CT practices on various aspects of soil health and it offers many of the same benefits as NT, including reduced soil erosion, increased SOM content, improved drainage and water holding capacity, and increased microbial and earthworm activity (Cooper *et al*., 2020). It has some advantages over NT in that there is less risk of soil compaction (due to periodic cultivations) and it can be used on a wider range of soil types. However, a recent assessment of CT and soil health based on a 5-year UK farm trial found that CT did not improve soil health or reduce diffuse water pollution compared to ploughing, although it did improve economic performance (Cooper *et al*., 2020).

In terms of soil carbon, NT or CT practices reduce soil disturbance and hence reduce the rate of SOM decomposition and release of carbon as CO_2 into the atmosphere. A review by Mehra *et al* (2018) concluded that the shift to NT systems was reducing the rate of decline in SOM because soil disturbance is minimal, and because crop residues are (often) left on the soil surface rather than being removed. However, Powlson *et al*. (2012) reviewed results from UK studies to quantify the impact changing from conventional to less intensive tillage on soil organic carbon (SOC) stocks. They concluded that the evidence for increased SOC stocks (as opposed to increased SOC concentrations near the soil surface) was "highly questionable", because the need for periodic inversion tillage (to control weeds and relieve compaction) would lead to SOC losses, which would counteract any gains accrued under the zero-tillage period. These authors also found that N_2O emissions may increase under reduced tillage systems, counteracting potential increases in SOC.

Importantly, Townsend *et al.* (2015) commented that throughout the literature, there is inconsistency in the impacts of adopting reduced tillage practices due to the variation in the practices used as well as the specific cropping systems, soil types and climate.

Summary of relevant legislation and government schemes (England)

- None identified

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** requires farmers to identify areas prone to run off and soil erosion, and adopt appropriate strategies to minimise these; the strategies include non-inversion cultivation.
- **Regenagri** cites CT (i.e. practices that minimize soil disturbance and maintain a significant portion of crop residues (usually at least 30%) on the soil surface to control erosion, preserve moisture, and promote soil health) as a regenerative crop production method.

Examples of relevant advice and guidance

- **CFE** suggest that introducing conservation agriculture (zero tillage plus continuous cover) can help improve soil physical condition and that run-off erosion risk can be minimised through direct drilling/strip tillage and/or under-sowing.
- The **COGAP** (Defra, 2009) suggests considering direct drilling or reduced tillage systems.
- Advice on using min-till or no-till farming is provided on the **Defra** website (https://defrafarming.blog.gov.uk/sustainable-farming-incentive-pilot-guidance-use-min-till-or-no-till-farming/)

5.4.2. Reduce soil loads

Brief evidence review

Farm machinery has become heavier over the years so that driving on fields can cause soil compaction and damage the soil structure. Low pressure tyres, dual wheels and reduced wheeling can all help to minimise soil compaction risks (Lilly *et al.,* 2018). Reducing soil loads was identified by German stakeholders as a key SSM practice (Strauss *et al*., 2023).

Tyre characteristics play an important role in relation to soil compaction; inflation pressure, wheel load, design and slip can all be managed to reduce the impact on soil structure (ten Damme *et al.*, 2020). Recent work in Denmark has demonstrated that modern large and low-ground pressure (LGP) tyres can help reduce soil stress to depths of 0.6 m (ten Damme *et al.*, 2019a). A nine-year UK/USA study also suggested that low pressure tyres can help to reduce compaction and boost crop yields (Harper Adams, 2021). Many farmers in the UK now use LGP tyres to reduce ground contact pressure; these tyres increase the footprint (contact area), which can improve traction and fuel economy as well as reducing the degree of topsoil compaction (Chamen *et al.,* 2015). Keeping applied pressure low will allow most roots to grow enough for crops to alleviate compression caused in dry to moist conditions. However, in wet conditions even LGP tyres will cause wheel slippage, smearing and compaction. Moreover, reductions in topsoil compaction resulting from the use of LGP tyres can be offset by increases in subsoil compaction, as farmers are able to increase loads and access land during wetter conditions (Chamen *et al*., 2015).

Repeated wheeling is known to lead to subsoil compaction, with multiple passes at high traction causing the most detrimental effects at depth (see for example ten Damme *et al*, 2019b; Pulido-Moncada *et al*, 2019). A study in Poland found that tractors with dual wheels exert much lesser pressure and cause smaller increases in soil density than tractors with single wheels (Blaszkiewicz, 2019). The use of tracks, particularly on harvest machinery of late harvested horticultural crops can reduce the depth of compaction, although not necessarily shallow compaction (Godwin & Spoor, 2015).

Summary of relevant legislation and government schemes (England)

- **Defra** provides advice for **SFI** participants on identifying, reducing and preventing soil compaction, although it states that “heavier machinery can cause widespread subsoil compaction down to 60 cm depth, even if you spread the load with low pressure tyres”. (https://defrafarming.blog.gov.uk/sustainable-farming-incentive-pilot-guidance-remove-soil-compaction/)

Summary of voluntary schemes and initiatives (England)

- None identified

Examples of relevant advice and guidance

- **CFE** suggest minimising compaction risks by using appropriate tyres and tyre pressures.
- Reducing ground pressure by using larger tyres and low inflation pressures is recommended in the **AHDB Beef and Sheep Manual 3** (Improving soils for Better Returns).
- The **COGAP** (Defra, 2009) states that if travelling on wet soils, loading should be reduced by using low ground pressure setups, or setting tyre pressures at the lowest that is compatible with the load and tyre type.

5.4.3. Control trafficking/manage tramlines

Brief evidence review

Farm machinery has become heavier over the years so that driving on fields can cause soil compaction and damage the soil structure. Controlled traffic farming (CTF) restricts farm machinery to fixed tramlines, reducing the area of the field at risk of compaction, whilst careful consideration of the timing of farm operations can avoid trafficking on soils when they are at their most vulnerable (see Section 5.1.2, Section 5.4.3 and Section 5.4.7). Managing over-winter tramlines was identified as a measure to manage SOM by Bhogal *et al.* (2009) by helping to prevent soil erosion. Compacted soil in tramlines can act as flow pathways increasing surface run-off; avoiding their use in winter can reduce run-off volumes and prevent the down-slope transport of sediment and nutrients. If tramlines are required then tines can be used to disrupt the tramlines and increase surface roughness to encourage water infiltration (see Section 5.4.7), or they can be superimposed on the drilled crop.

A comprehensive review of the effects/implications of CTF in arable and grass cropping systems on overall soil health, crop performance and yield, fertilizer and water use efficiency, and GHG emissions was undertaken by Antille *et al.* (2019). The review found evidence that by reducing the area subject to soil compaction, CTF had beneficial impacts on overall soil health with respect to improved water infiltration, reduced erosion and runoff rates, better soil structure and higher numbers of earthworms.

In the UK, Chamen *et al*. (2015) found that restricting the loading of soils to the smallest possible area will limit the extent of deep soil compaction, whilst a literature-based evaluation of CTF by Mouazen & Palmqvist (2015) estimated that it reduced soil compaction by 24% and tillage energy requirement by 10%; and improved fertiliser use efficiency by 3%. In addition, CTF was estimated to enhance soil biodiversity (7%), erosion control (6%) and SOM (6%); and reduce greenhouse gas (GHG) emissions by 3%.

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that land managers must take reasonable precautions to prevent significant soil erosion and runoff from land management and cultivation practices (such as seedbeds, tramlines, rows, beds, stubbles (including harvested land with haulm), polytunnels and irrigation).
- **Countryside Stewardship:** RP31 is for equipment to disrupt tramlines in arable areas. This is to support the purchase of equipment that can loosen soil that has compacted in wheeled tramlines, helping reduce surface runoff, risk of soil erosion damage and water pollution.
- **Defra** provides advice for **SFI** participants on using controlled traffic farming (Use controlled traffic farming - Farming (blog.gov.uk)

Summary of voluntary schemes and initiatives (England)

- None identified

Examples of relevant advice and guidance

- **CFE** suggest considering controlled traffic approaches and avoiding traffic on soils when they are beyond the plastic limit in top 40 cm.
- Controlled machinery trafficking is recommended in the **AHDB Beef and Sheep Manual 3** (Improving soils for Better Returns).
- The **COGAP** (Defra, 2009) provides various pieces of advice on managing tramlines and trafficking.

5.4.4. Reduce frequency/depth of ploughing

Brief evidence review

Making changes to the ploughing regime by reducing the frequency and/or depth of ploughing was suggested by several sources in the literature as an SSM.

Reducing ploughing frequency will clearly reduce soil loads and offer some of the benefits (and problems) associated with reduced tillage systems (Section 5.4.1 and Section 5.4.2). The effect of reducing the depth of ploughing is less clear. Ploughing is often used as a way to improve soil structure by breaking up consolidated/compacted soil; however by disturbing the soil and exposing it to the air, ploughing can lead to losses of SOM.

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that land managers must take reasonable precautions to prevent significant soil erosion and runoff from land management and cultivation practices (such as seedbeds, tramlines, rows, beds, stubbles (including harvested land with haulm), polytunnels and irrigation).

Summary of voluntary schemes and initiatives (England)

- None identified

Examples of relevant advice and guidance

- The **COGAP** (Defra, 2019) advises not cultivating more deeply than is necessary.

5.4.5. Cultivate/loosen compacted soil

Brief evidence review

Cultivating compacted arable soils (by ploughing or subsoiling) and loosening compacted soil layers in grassland fields (by aerating, subsoiling or using a sward slitter or sward lifter) were identified by Bhogal *et al*. (2009) as best practice methods for SOM management. These techniques can break up hard pans which prevent water infiltration into the soil, thereby reducing the risk of surface runoff and sediment/nutrient losses, and encouraging plant roots to penetrate deeper soil layers. However, soil loosening may weaken the soil structure and on tillage land increase the risk of erosion from subsequent rainfall events (or wind erosion on fine/light soils). Reconsolidating soil after loosening (using a roller) to avoid erosion issues was identified by some German stakeholders as a potential SSM practice (Strauss *et al*., 2023).

There have been many reviews of the effects of compaction on soils, crops and the wider environment and there is little doubt as to the benefits of alleviating compaction, although effectiveness varies considerably depending on initial levels of compaction and soil conditions at the time of alleviation (Chamen *et al*., 2015). In terms of different methods that can be used, an interesting literature review funded by Defra and the Scottish Government undertaken by Chamen *et al*. (2015) located a large amount of evidence on the threat posed by soil compaction and on mitigation strategy effectiveness (subsoiling, targeted subsoiling and ploughing). The effectiveness of mitigation strategies was found to vary considerably depending on the extent and depth of compaction, climate and soil type, with the authors concluding that overall subsoiling was less effective than many farmers perceived. Newell-rice *et al.* (2014) investigated the effect of (shallower – c. 20cm and deeper – c. 30cm) mechanical loosening and the introduction of deep-rooting herbs and legumes in alleviating soil compaction at four grassland sites in England and Wales. They found that mechanical loosening resulted in 4- to 10-fold increases in water infiltration rates that persisted for at least 30 months post-loosening, with deeper loosening resulting in greater increases in water infiltration rates than shallower loosening. However, within the time frame of the study (four years), the herb and legume seed mix had no effect on water infiltration rates. In fact, power-harrowing carried out to establish the seed mix tended to suppress water infiltration.

It is extremely important to check whether subsoiling is really necessary and that the soil type is appropriate. Subsoiling and other loosening operations should be avoided when the soil is wet as this can cause further structural damage. Careful attention should be paid to soil and weather conditions to avoid re-compaction problems when rolling and during following cultivation or trafficking (Ghosh & Daigh, 2020). It is also advisable to plant a crop after subsoiling to stabilise the soil and reduce the risk of erosion (see Section 5.3.1).

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that the land manager must ensure that reasonable precautions are taken to prevent agricultural diffuse pollution resulting from land management and cultivation practices on agricultural land. Reasonable precautions include breaking up compacted soil.

- **Countryside Stewardship:** RP31 is for equipment to disrupt tramlines in arable areas. This is to support the purchase of equipment that can loosen soil that has compacted in wheeled tramlines, helping reduce surface runoff, risk of soil erosion damage and water pollution.
- Advice for **SFI** participants on reducing and alleviating compaction is provided on the **Defra** website (https://defrafarming.blog.gov.uk/sustainable-farming-incentive-pilot-guidance-remove-soil-compaction/).

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** requires soil on organic farms to be managed to enhance stability, SOM levels and soil structure and to prevent compaction, erosion and run-off.
- **Leaf Marque** states that there should be no significant visual evidence of soil damage such as compaction, and that a soil management plan must include areas prone to compaction.

Examples of relevant advice and guidance

- **CFE** suggest aerating pasture if there is evidence of surface compaction (but choose the right machinery) and taking a targeted approach to address compaction directly through sub-soiling as needed in the right conditions.
- The **Code of Good Agricultural Practice for Reducing Ammonia Emissions** states that slurries and other liquid organic manures should only be applied to soils that support infiltration (such as not saturated or very compacted) to minimise both air and water pollution.
- The **COGAP** (Defra, 2009) advises soil loosening or sub-soiling when soils are dry (but not hard) to depth.
- In the checklist for decision making **RB209** (AHDB, 2019) advises farmers to assess soil structure and take action to remove soil compaction if necessary.
- Advice on recognising and dealing with compaction is given in the **AHDB Beef and Sheep Manual 3** (Improving soils for Better Returns).

5.4.6. Leave autumn seedbeds rough

Brief evidence review

Leaving autumn seedbeds rough was identified in the literature sources as a method for managing SOM (Bhogal *et al*., 2009) and reducing soil erosion risks (Boardman, 2017). Sowing winter cereals in autumn risks leaving a large proportion of the soil surface bare and susceptible to overwinter erosion losses. Soil surface roughness is important as it affects water storage capacity and infiltration rates, interception of overland flow, and ultimately sediment detachment and erosion. A rough soil surface with larger soil aggerates reduces the susceptibility of soils to wind and water erosion and will also prevent the sandy and light silty soils from ‘capping’.

A laboratory-based rainfall simulation experiment using a silty clay loam soil in Belgium found that increasing surface roughness increased the time taken to initiate surface runoff and reduced the total amount of runoff (Vermang *et al*., 2015). However, the effect diminished over time due to aggregate breakdown and the formation of thick depositional seals on the soil surface. Sediment concentration increased with increasing soil surface roughness, due to runoff being channelled into flow paths. Final soil loss rates were similar for all soil roughness categories, indicating that roughness is important in influencing runoff rates and the time to initiate runoff, but not in influencing sediment export through soil loss rates. Field-based evidence on the effects of surface roughness is scarce, although Evans

(2017) reported that no erosion or runoff was recorded over a 10-year period on 7 fields in Norfolk with rough bare soils that stored incoming rainfall and/or rainfall rapidly infiltrated.

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that reasonable precautions must be taken to prevent significant soil erosion and runoff from land management and cultivation

Summary of voluntary schemes and initiatives (England)

- None identified

Examples of relevant advice and guidance

- The **COGAP** (Defra, 2009) advises that a coarse seedbed will reduce the risk of the soil slumping or capping which can reduce emergence and lead to run-off and erosion. In addition, it recommends that land should be left in stubble (or roughly cultivated) over winter to minimise run-off and erosion before spring sown crops.

5.4.7. Avoid root crop/vegetable harvest on wet soils

Brief evidence review

Severe soil compaction problems can be caused when root crops and vegetables are harvested from soils at or wetter than field capacity (Batey, 2009), so avoiding this practice will be beneficial for SSM.

An example from England was provided by Evans (2017) who studied the factors controlling soil erosion and runoff and their impacts in the upper Wissey catchment, Norfolk over a 10-year period. Whilst runoff and erosion took place a number of times in a year from a range of autumn- and spring-sown crops, it occurred dominantly down tractor wheelings or ruts left after harvesting potatoes or sugar beet in wet conditions. Also, Palmer & Smith (2013)-in their survey of soil structural condition of soils in 24 catchments in SW England found that a high proportion of soils growing late harvested crops (maize/potatoes) had evidence of severe degradation.

Elsewhere, Thorsoe *et al*. (2019) identified what they referred to as 'problematic traffic situations' on Danish farms. These included root crop harvesting which involves a high wheel load (see Section 5.4.2) and is often carried out when the soil water content is high, incurring a high risk of subsoil compaction, particularly on heavier soils.

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that land managers must take reasonable precautions to prevent significant soil erosion and runoff from land management and cultivation practices (such as seedbeds, tramlines, rows, beds, stubbles (including harvested land with haulm), polytunnels and irrigation)

Summary of voluntary schemes and initiatives (England)

- None identified

Examples of relevant advice and guidance

- **CFE** suggest that traffic on soils when they are beyond the plastic limit in the top 40 cm should be avoided.

- **RB209** (AHDB, 2019) guidance states that developing and maintaining a good soil structure depends greatly on good soil management, including cultivation at appropriate times and depths and minimising traffic over the soil when it is too wet.
- The **COGAP** (Defra, 2009) advises against harvesting in conditions when equipment leaves ruts in fields.

Table 9. Table of SSM measures currently used or with potential for use in the UK: measures related to mechanical pressures and cultivation methods. (G: Grass; A: Arable; H: Horticulture)

SSM measure	Relevance (G/A/H)	Main threat(s) addressed	Benefits	Risks/issues	Context/comments
No tillage	A	Loss of SOM Erosion	• Increases SOM • Reduces erosion risk	• Can cause compaction • SOM only increases in top 10 cm	Not suitable for all soils/climatic conditions. Cover crops can alleviate some issues
Minimum/reduced tillage*			• Increases SOM • Reduces erosion risk • Can be used more widely than no-till	• SOM may be lost when soil is cultivated	
Reduce soil loads	A/G	Compaction Erosion	• Reduces compaction risk • Reduces erosion risk		Benefits depend on the specific changes made to machinery and trafficking frequency
Control trafficking/manage tramlines**			• Reduces area at risk of compaction • Reduces erosion risk • Better overall soil health		
Reduce frequency/depth of ploughing	A	Erosion	• Reduces soil disturbance • Reduces erosion risk • Increases SOM	• Increased risk of soil compaction • Deep ploughing can protect SOC from loss	Effects of ploughing on SOC are site/soil specific
Cultivate/loosen compacted soil***	A/G	Compaction Erosion	• Reduces compaction risk • Reduces erosion risk	• May cause (further) damage if undertaken on wet soils or soils in good condition	Planting a cover crop after subsoiling can stabilise the soil and reduce the risk of erosion
Leave autumn seedbeds rough	A	Erosion	• Reduces erosion risk • Reduces capping		
Avoid root crop/vegetable harvest on wet soils	A/H	Compaction Erosion	• Reduces compaction risk • Reduces erosion risk		Particularly important on heavier soils Has implications for the supply of vegetables and potatoes using current supply chains

*Including strip tillage, conservation tillage etc

**Including avoiding headland compaction

***Including subsoiling and pasture aeration

5.5. SSM measures relating to the physical environment.

5.5.1. Adapt cultivation to topography (cross slope cultivation)

Brief evidence review

Furrows and tramlines orientated down the slope will tend to collect water and develop concentrated surface flow paths leading to soil erosion. Cultivating and drilling across the slope will reduce the risk of sheet and rill flow developing, as the ridges created across the slope increase down-slope surface roughness and provide a barrier to surface run-off. Soils cultivated across the slope will also hold more water in surface depressions. Adapting cultivation to topography (by cross slope cultivation or contour ploughing) was identified by several literature sources as an SMM measure, a method for SOM and a regen agricultural principle.

Adapting cultivation practices to meet topographical constraints is widely practiced across the world as a method for preventing or reducing soil erosion, and many papers have been published on this topic. In the UK, Posthumus *et al.* (2015) found that contour ploughing was one of the most cost-effective erosion control measures available (based on an ecosystem services approach) however they warned that it is "not appropriate in all circumstances and therefore cannot be widely promoted". In contrast, in their study of soil erosion in the South Downs, Boardman *et al.* (2017) reported that some changing practices, such as along-the-contour-working, may be of little value in terms of reducing erosion risks; they also identified the need to avoid headland compaction as an important method for reducing soil erosion risks.

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that land managers must take reasonable precautions to prevent significant soil erosion and runoff from land management and cultivation practices (such as seedbeds, tramlines, rows, beds etc.).

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** requires farmers to identify areas prone to run off and soil erosion, and adopt appropriate strategies to minimise these; the strategies include contour cultivation.

Examples of relevant advice and guidance

- The **COGAP** (Defra, 2009) advises ploughing or cultivating across the slope.

5.5.2. Cross slope barriers/beetle banks

Brief evidence review

Cross-slope barriers are soil and water conservation measures that are created on sloping lands in the form of earth or soil bunds, stone lines, and/or vegetative strips/barriers (usually grass). By reducing the steepness and/or the length of the slope, these techniques therefore contribute to soil, water, and nutrient conservation. Beetle banks can also be strategically placed across slopes of fields prone to surface run-off to improve infiltration and reduce the risk of soil erosion whilst providing a valuable habitat for wildlife, including beneficial insects. Cross slope barriers were recommended by some German stakeholders (Strauss *et al*., 2023) as an SSM.

There have been some reviews published on the effectiveness of cross-slope barriers at reducing run-off and erosion but none that we could locate were pertinent to UK agroclimatic conditions. However, beetle banks were one of the erosion mitigation methods considered by Boardman *et al* (2017), although only one farmer in the South Downs study area had actually introduced them. The literature on their use as an SSM method is very limited.

Summary of relevant legislation and government schemes (England)

- **Countryside Stewardship:** AB3 is for beetle banks.
- Advice for **SFI** participants on creating and maintaining beetle banks is provided on the **Defra** website (https://defrafarming.blog.gov.uk/create-and-maintain-beetle-banks/).

Summary of voluntary schemes and initiatives (England)

- **Regenagri** includes the installation of beetle banks as a potential means of enhancing biodiversity.

5.5.3. Field or riparian buffer strips

Brief evidence review

Buffer strips are strips of vegetation within a field or alongside a river that provide a physical barrier which helps slow the flow of water and runoff from fields into adjacent watercourses. They act to reduce soil erosion and nutrient losses, improve water quality and provide a habitat for wildlife. Buffer strips are mentioned by many of the literature sources as an SSM.

Buffer strips have been widely studied and their benefits for a range of ecosystems services were recently reviewed by a team of UK researchers (Cole *et al*., 2020) who also provided recommendations for best management practices. In terms of their effectiveness at reducing erosion risks, Posthumus *et al.* (2018) concluded that buffer strip were among the most cost-effective erosion control measures in the UK, although Boardman *et al.* (2017) reported that they were not always effective, with one farmer in the South Downs study area commenting that "if you've got a soil erosion problem, it comes off the whole field and it'll go straight over a buffer strip, it won't hold it back". Recently, Boardman & Vandaele (2023) reiterated the importance of buffer strips as a method for interrupting connectivity between fields and receiving waters, especially on sites with high erosion risk.

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that land managers must take reasonable precautions to prevent significant soil erosion and runoff from land management and cultivation practices Reasonable precautions include grass buffer strips in valleys, along contours, slopes, field edges or gateways.
- **SFI**: AHL4 and IGL3 relate to 4-12m buffer strips on arable and horticultural land and improved grassland, respectively, to "prevent pollutants, such as sediment and nutrients, from being carried in surface water runoff, if located next to a watercourse".
- **Countryside Stewardship:** SW1-4 relate to buffer strips and in-field grass strips.

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** requires notification if buffer strips are removed, and the farmer must demonstrate that the change will have a positive (or not negative) impact on the identified conservation value.
- **Regenagri** includes the establishment of buffers around watercourses as one of their key practices for reducing nutrient pollution of watercourses and enhancing biodiversity.

- **Certified Regenerative** states that buffer strips should form part of the regenerative plan and must be optimised to remove nutrients from erosion. They should be set up alongside watercourses and reservoirs to protect biodiversity and soil erosion.
- **Pasture for Life** notes that areas of rough grass can help slow down run-off from fields, buffer important features and provide habitat for small mammals and beneficial insects.

Examples of relevant advice and guidance

- **CFE** recommend incorporating designed buffer strips alongside watercourses, ditches and hedges to manage run-off.

5.5.4. Introduce trees/hedges

Brief evidence review

Introducing trees or hedges into otherwise featureless fields will help to stabilise the soil, reduce the risk of erosion and sequester additional carbon. Trees and hedges will offer some of the benefits of agroforestry/silvopasture systems (see Section 5.2.6) by providing shelter for livestock, and food and corridors for wildlife. They can reduce the need for pesticides and enhance the visual aesthetics of rural landscapes.

Hedgerows and hedgerow soils have been extensively researched in recent years. Two recent UK reviews serve as good examples of the general findings. Montgomery *et al* (2020) and Holden *et al.* (2019) both reported that one of the main functions of hedgerows was soil protection and that there was evidence that hedgerows soils provide a number of ecosystem services including storing organic carbon, promoting water infiltration and storing runoff, increasing earthworm diversity, and hosting distinctive communities of mycorrhizal fungi and microarthropods.

Summary of relevant legislation and government schemes (England)

- **The Hedgerows Regulations 1997** protect 'important' hedges
- **The Management of Hedgerows (England) Regulations 2024** provide a consistent approach for hedgerow protection across England. They include:
    - a 2-metre buffer strip, measured from the centre of a hedgerow, where a green cover must be established and maintained. Also, no cultivation or the application of pesticides or fertilisers should take place within this buffer strip
    - a hedgerow cutting ban from 1 March to 31 August (inclusive)
- **SFI**: HRW2 and HRW3 relate to managing hedgerows, and maintaining and establishing hedgerow trees. TE4 is to supply and plant trees.
- **Countryside Stewardship:** BN5-11 relate to hedgerow creation and management.

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** requires notification if hedges are removed, and the farmer must demonstrate that the change will have a positive (or not negative) impact on the identified conservation value.
- **Regenagri** includes the installation of hedgerows and windbreaks (living fences) to help move wind above ground level helping prevent soil erosion, increase yields, reduce nutrient losses and improve soil health.

- **Leaf Marque** requires that in-field trees and trees in boundaries and hedgerows are retained and managed appropriately, and that 10% or more of the farm is manged as a habitat area (including hedges).
- **Pasture for Life** encourages the introduction of hedgerow trees to act as a windbreak, and gives a number of recommendations for managing hedgerows and field margins.
- **Biodynamic certification** recommends the creation of a diverse ecosystem within and around the crop; this can include leaving uncultivated field margins, hedges, windbreaks and wildlife corridors.

Examples of relevant advice and guidance

- **CFE** suggest introducing trees as shelter belts, hedges and in wood pasture.

5.5.5. Set aside of marginal/sensitive land

Brief evidence review

Setting aside marginal or sensitive areas of land offers many of the same benefits (and issues) as arable reversion to grassland (albeit on a smaller scale) or leaving land fallow in terms of improved carbon storage and SOM content, biodiversity and reduced compaction and erosion risks (see Sections 5.3.6 and 5.3.11).

Summary of relevant legislation and government schemes (England)

- **SFI**: AHL3 relates to grassy field corners or blocks and aims to maintain a year-round grass cover without compacted areas or poaching.

Summary of voluntary schemes, initiatives and advice (England)

- None identified

5.5.6. Appropriate drainage (maintain drains)

Brief evidence review

One of the principles of SSM as defined by the FAO is to "Improve soil water management so that water is efficiently infiltrated and stored to meet the requirements of plants and ensure the drainage of any excess". Creating an appropriate field drainage system by maintaining drains and/or mole ploughing will remove excess water from the soil and reduce or eliminate waterlogging. The lack of oxygen in soils as a result of prolonged surface waterlogging can have a significant impact on soil physical, chemical and biological properties with implications for crop growth and productivity. Draining and drying waterlogged soils can reverse these impacts to some extent. Another method is to use swales (shallow grass-lined channels), which are designed to collect water and move it gradually away downslope, allowing water to infiltrate along their route and grass to help filter out suspended sediments and take up nutrients. Soils in a well-drained state are usually easier to work and less prone to damage from poaching or trafficking.

Drainage and drainage systems have been investigated for many years. Balshaw *et al*. (2014) comprehensively reviewed this subject, including an assessment of the effectiveness of different practices for preventing and alleviating damage caused by waterlogging. The Field Drainage Guide (Hill *et al*., 2015) describes how improving drainage has numerous benefits for soils including:

- Improved soil fertility due to faster warming of soils, improved environment for soil organisms, better plant root access to water and oxygen and better uptake of soil mineral N.
- Reduced livestock poaching.
- Reduced surface run-off and erosion, and phosphorus and pesticide losses.

However, drainage systems can accelerate the delivery of agricultural pollutants from land to a watercourse, by acting as a preferential (by-pass) flow route (Bhogal *et al*., 2009).

Note: Allowing drains to deteriorate (or blocking drains) will increase soil wetness and reduce the rate of SOM oxidation. This might be classed as an SSM method for lowland peaty/organic soils, for wetland restoration and for low input grassland, but it is not applicable to tillage land where economically sustainable arable cropping is a requirement. Leaving fields undrained may necessitate arable reversion to grassland (see Section 5.3.11) or possibly paludiculture (see Section 5.6.5).

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that land managers must ensure that reasonable precautions are taken to prevent agricultural diffuse pollution resulting from land management and cultivation practices on agricultural land, including installing drainage.
- **SFI**: LIG1 and LIG2 state that drainage work should not be undertaken on low input grasslands.
- **Countryside Stewardship**: RP11 is for swales and RP5 for cross drains.

Summary of voluntary schemes and initiatives (England)

- **Leaf Marque** requires maps of all drainage for farm buildings and land.

Examples of relevant advice and guidance

- **CFE** suggest that farmers ensure drains are present and maintained where needed to maintain soil physical condition.
- The **Code of Good practice for Reducing Ammonia Emissions** states that deep (slurry) injectors should only be used when the soil is sufficiently dry and not on land with a drainage system in order to prevent water pollution.
- The **COGAP** (Defra, 2009) recommends regular inspection of soils to indicate whether drains need to be maintained or replaced.
- Advice on maintaining field drainage is given in the **AHDB Healthy Grassland Soils** booklet
- The Field Drainage Guide is available on the **AHDB** website (https://ahdb.org.uk/drainage)

5.5.7. Hard tracks for stock movement.

Brief evidence review

Cow tracks are important for allowing a herd to move safely and comfortably around a farm. They also allow a longer grazing season and reduce poaching and compaction damage to soils, although this was not specifically mentioned as an SSM in the literature and there is a lack of published evidence to support any beneficial effects on soils.

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) state that land managers must ensure that reasonable precautions are taken to prevent agricultural diffuse pollution resulting from land management and cultivation practices on agricultural land. These include creating farm tracks.
- **Countryside Stewardship**: RP4 is for livestock and machinery tracks with the aim of protecting water quality by reducing poaching.

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** requires that tracks and gateway are at least 3.5m wide to allow stock to move freely.
- **Leaf Marque** requires that measures are taken to avoid damage to grassland by livestock and to optimise biodiversity, including consideration of permanent tracks.

Examples of relevant advice and guidance

- **CFE** suggest installing hard track systems for stock movement.
- Advice on cow tracks is available on the **AHDB** website (https://ahdb.org.uk/knowledge-library/cow-tracks)
- Using dedicated tracks for machinery and moving stock is recommended in the **AHDB Beef and Sheep Manual 3** (Improving soils for Better Returns).

Table 10. Table of SSM measures currently used or with potential for use in the UK: measures related to the physical environment. **(G: Grass; A: Arable; H: Horticulture)**

SSM measure	Relevance (G/A/H)	Main threat(s) addressed	Benefits	Risks/issues	Context/comments
Adapt ploughing to topography (cross slope cultivation)	A	Erosion Loss of SOM	• Reduces risk of erosion by water • Prevents loss of SOM		Not appropriate in all circumstances
Cross slope barriers/beetle banks	A	Erosion Biodiversity	• Reduces risk of erosion by water • Provides a habitat for wildlife		
Field or riparian buffer strips	A/H	Erosion Biodiversity	• Reduces risk of erosion by water • Reduce nutrient losses • Provides a habitat for wildlife		
Introduce trees/hedges	G/A	Erosion Biodiversity Loss of SOM	• Stores organic carbon • Promotes water infiltration and stores runoff, • Increases soil biodiversity.		
Set aside of marginal/sensitive land	G/A/H	Loss of SOM Compaction Erosion Biodiversity	• Reduces risk of soil compaction and erosion • Enhances biodiversity • Increase SOM		
Appropriate drainage (maintain drains)*	G/A/H	Erosion	• Improved soil fertility. • Reduced livestock poaching. • Reduced surface run-off and erosion • Reduced phosphorus and pesticide losses.		
Hard tracks for stock movement	G	Compaction Erosion	• Reduced poaching and compaction	• May accelerate nutrient delivery to watercourses	

*Including mole ploughing

5.6. SSM measures relating to soil testing and monitoring, education and advice.

5.6.1. Local soil monitoring and testing

Brief evidence review

Providing farmers and advisers with the means for monitoring and interpreting soil conditions at field scale can support benchmarking and best practice (Ingram & Mills, 2018). Regular soil monitoring and testing is widely recognised as being imperative to the successful delivery of SSM, and is recommended in many of the regulations and voluntary schemes in place in the UK. Such is the importance placed on soil testing in the EU that as part of the EU Soil Strategy for 2030 the Commission will assist Member States to set up a "test your soil for free" initiative, to provide farmers and other actors with information to help them to better understand the health of their soil (EC, 2021). More recently, the EU proposed a new Soil Monitoring Law to protect and restore soils and ensure that they are used sustainably (EC, 2023).

Summary of relevant legislation and government schemes (England)

- The **FRfW** (SI, 2018) include a requirement to test soils at least every 5 years to inform planning for applying manures and fertilisers.
- **SFI**: SAM1 relates to assessing soil, producing a soil management plan and testing SOM.

Countryside Stewardship requires that manure and fertiliser applications are planned, using the results of soil tests (pH and nutrients), and grant applications should be supported by soil sampling and analysis where appropriate.

Summary of voluntary schemes and initiatives (England)

- The **Soil Association** may require evidence that soil fertility is being maintained; this may be through soil testing results and/or yield records.
- **Regenagri** requires soil analysis as a key element of regenerative agriculture.
- **Leaf Marque** requires a nutrient management plan including regular soil testing.
- **Fair to Nature** requires that a soil management plan is completed annually, including records from soil monitoring (at least one of SOM testing, Visual Evaluation of Soil Structure or earthworm counts) and management undertaken to address issues identified.
- **Pasture for Life** recommends that farm level soil health monitoring should be carried out (this could include earthworm counts, slake testing, SOM tests, digging soil pits and similar activities.)

Examples of relevant advice and guidance

- **CFE** suggest that everyone should use soil testing regularly to optimise fertiliser and lime use (pH, P, K, Mg).
- Advice on sampling for soil analysis is given in **RB209** (AHDB, 2019).
- Advice on soil sampling and testing is given in the **AHDB Beef and Sheep Manual 3** (Improving soils for Better Returns).

- The **AHDB soil health scorecard** is an online excel tool where farmers can benchmark basic metrics (https://ahdb.org.uk/knowledge-library/the-soil-health-scorecard)
- The **Code of Practice for Reducing Ammonia Emissions** state that a nutrient management plan and regularly testing of manure and soil should be used to calculate suitable application rates and plan timing.
- The **COGAP** (Defra, 2009) recommends looking at soil structure in each field and sampling soil for pH and nutrients, as part of farm soil and nutrient management plans.

5.6.2. National scale soil monitoring

Brief evidence review

One of the UN's six principles of SSM was to develop knowledge systems (see Section 3.1) including "Test, classify and map soils. Integrate existing data and provide specific fertility and management recommendations by crop and soil type" and monitoring soil is clearly key to supporting sustainable management decisions at both a national and local level (Keestra *et al*., 2023).

Much has been written about national (and European) scale soil monitoring and its importance for detecting changes in various soil properties, functions and overall soil quality/health, and it is outside the scope of this study to review this here. However, it is worth noting the soil monitoring programmes that currently operate in or cover the UK: links to some of these can be found via the UK Soil Observatory website together with a soil data map viewer (https://www.ukso.org/quick-links.html). The main programmes and datasets pertinent to agricultural soil in England are:

- The **UKCEH Countryside Survey** (1978- present) measures a range of properties in soil cores taken from 629 monitoring locations every 5 years. Measurements include soil physical condition (bulk density, aggregate stability), acidity and nutrient status (pH, N, P), contaminants (including PTEs and persistent organic pollutants), biodiversity (bacterial and fungal diversity, mesofauna abundance and diversity), soil functions (potential N mineralisation, nitrification rates, basal respiration rates, carbon substrate utilisation rates, water holding capacity).
- The 12 **UK Environmental Change** Network (ECN) terrestrial sites are part of a long-term environmental monitoring programme. Soil solution chemistry data (1992-2015) include pH, conductivity, alkalinity, Al, Ca, chloride, ammonium-N, nitrate-N, phosphate-P, K, sulphate-S, Na, total N and total dissolved P.
- The **National Soil Moisture Network (COSMOS-UK)** provides data showing how soil moisture varies across the country with soil type, climate and vegetation.
- The British Geological Society (BGS) **Advanced Soil Geochemical Atlas for England and Wales** (Rawlins *et al*., 2012) presents analyses and maps of soil concentrations for 53 elements based on data collected for the National Soil Inventory (NSI) between 1978 and 1982.
- The **Geochemical Baseline Survey of the Environment (G-BASE)** is the BGS systematic geochemical baseline programme (soils samples collected 1986-2014). Concentrations of 50 chemical elements were determined.
- The **National Soil Map of England and Wales (NATMAP)** holds information on various soil properties for 297 soil series; it forms the basis for the Agricultural Land Classification system.
- The **UK Soil and Herbage Pollutant Survey (UKSHS)** aimed to establish a baseline for pollutant levels in soil and herbage from 122 rural, 28 urban and 50 industrial sites across the UK.
- The **England Ecosystem Survey (EES)** is part of Defra's Natural Capital and Ecosystem Assessment Programme which aims to gather nationally representative data to help assess

the state of England's ecosystems. The survey covers 500 areas, each 1 km^2 called 'monads', which are distributed across England; each monad is surveyed for soil quality indicators, vegetation and landscape, as well as a thorough soil classification assessment.

Some surveys undertaken at the European scale also include data for the UK:

- The **LUCAS Topsoil Survey** harmonizes topsoil sampling and analytical procedures across the EU. Soil properties measured include pH, organic carbon content, $CaCO_3$, N, P, K, electrical conductivity, oxalate extractable Fe and Al, texture, PTEs, erosion assessment, depths of organic soils, biodiversity and plant protection products.
- The **Geochemical Mapping of Agricultural and Grazing Land Soil of Europe (GEMAS)** project collected over 4000 agricultural and grazing land soil samples from 33 European countries and measured concentrations of 50 chemical elements.
- The **FOREGS (Forum of European Geological Surveys)** Geochemical Baseline Mapping Programme was initiated in 1998 to provide high quality environmental geochemical baseline data in Europe.

Whilst national scale soil monitoring is extremely valuable as a source of data for researchers and can be used by policy makers as a tool to track the performance of policy initiatives, it is unlikely to be widely used by individual farmers or advisors as user-friendly interfaces and access methods are not always available. An exception is the Soil Site Reporter (https://www.landis.org.uk/services/soil-site-reporter.html) which uses NATMAP data to produce a range of maps, graphs and schematic diagrams to help describe the soils and their properties at a specified point, although the reports are chargeable. Another examples is the new free web tool, SOil funDamentals (SOD), designed to help landowners monitor and improve the health of their soils which was developed using data from the UKCEH's nationwide Countryside Survey (https://www.ceh.ac.uk/news-and-media/news/new-web-tool-measuring-health-soils) and which compares some key soil metrics (pH, OM, earthworm numbers and bulk density) with observations from similar habitats, Figure 10.

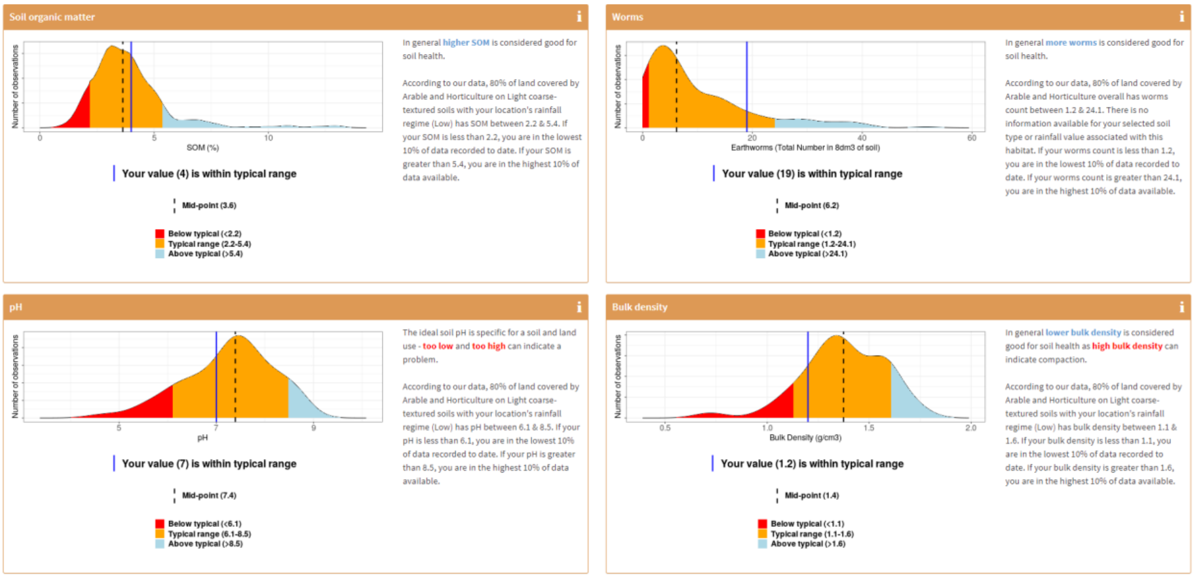

Figure 10. Outputs from the Soil funDamentals tool.

5.6.3. Education and advice

Bried evidence review

The six principles set out by the UN for Sustainable Soil Management (UN, 2016) include 5. Develop extension services, knowledge systems and promote innovation and 6. Communicate the importance of soil (Figure 4). However, as we commented earlier in this report (Section 3.1), these aspects seem largely to have been overlooked in subsequent definitions of SSM and in much of the research that has been undertaken to assess how we can effectively achieve SSM. If farmers and their advisors are not provided with sufficient scientifically robust evidence or if advice is not communicated clearly and effectively, then it is not surprising that they might be unwilling or reluctant to adopt SSM measures, regardless of how effective they might be from a scientific perspective.

An increasing number of social science-based research studies are being undertaken that are seeking to better understand the attitudes of farmers and land managers towards various SSM practices and the factors and barriers affecting their uptake (e.g. Rust *et al*., 2020). Various papers on this topic published between 2018 and 2020 have been collated for a Virtual Special Issue of the Soil Use and Management journal on 'Sustainable Soil Use and Management: Knowledge Sharing and Adoption Behaviour'. Broad topic areas covered included advisory services and workshops, information technology and social media, engaging with multiple stakeholders and multiple objectives, and adoption behaviour, with an introductory editorial provided by Hou (2020). It is not proposed to go into detail here as to the uptake and effectiveness of the various knowledge delivery routes and engagement options, but any attempt to deliver a policy goal of 'sustainable soil management' on a local or national basis should include measures related to the effective dissemination of knowledge, information and advice. These could comprise a mixture of:

- Soil-related training for farmers (e.g. workshops, webinars)
- Peer support networks (e.g. special interest groups)
- Information technology (e.g. decision support tools) and social media
- Extension services

As we have shown in the earlier sections of this report, some advice on SSM methods is available via the Defra and AHDB websites and in Codes of Practice, and via voluntary schemes and initiatives. A good example of effective knowledge transfer is the AHDB Monitor Farm network set up to offer support and guidance to growers looking to improve their businesses and learn from others. These offer regular open meetings (summer farm walks and winter discussion groups) led by each monitor farmer, for other local farmers to attend, learn best practices from industry experts and share their knowledge on key topics, such as soil health. It is debatable whether these resources are sufficient and fit for the purpose of supporting the wider uptake of SSM as a national policy. It has been argued that soil policy and advisory services in Europe are fragmented, and that delivery of advice is complicated by the multi-scale nature of SSM and the diverse audience (Ingram & Mills, 2018). The authors provide various suggestions for improvement including building closer links between researchers, advisors and farmers, providing examples of best practice, and supporting peer-to-peer and individual learning. An important point was the need to raise awareness of the value of soil and its many functions, so that the focus moves away from improving single soil functions, addressing a specific threat, or meeting individual regulatory or grant requirements, towards a more holistic perspective of the concept of SSM [see also Keestra *et al*. (2023) who argue for a more holistic approach to SSM because soil issues are complex and interrelated with wider societal concerns].

A potential model for the delivery of farmer advice is Catchment Sensitive Farming (CSF), the government funded advisory initiative for reducing the contribution of agriculture to diffuse water pollution. The effectiveness of the advice delivery in encouraging farmer engagement has recently been assessed by Chivers (2021), who also offered suggestions for how this could be improved.

5.7. Novel/untested SSM measures

5.7.1. Novel organo-mineral fertilisers

Brief evidence review

In response to rising energy costs and political instability affecting the price and supply of mineral fertilisers, farmers may increasingly seek alternative sources of crop nutrients. Consequently, there is increasing interest in developing technologies which recover, and re-use the nutrients contained in organic materials and other 'waste' materials from the food chain, turning them into products with properties more consistent with those of conventional fertilisers. A recent rapid evidence review undertaken for Defra on these 'novel' fertiliser products (Bhogal *et al*., 2022) concluded that whilst there are a number of technologies which can either potentially enhance the nutrient use efficiency of existing materials applied to land or improve their handling properties, there was considerable uncertainty on the crop available nutrient content (and hence fertiliser replacement value) of many of the processed materials.

In addition to uncertainties over their nutrient supply properties, evidence on benefits to soil is also limited, although they can be expected to supply OM and benefit soils in a similar way to other organic materials (see Section 5.1.1). Some research on this topic is already underway in the UK. For example, a recent field study tested 3 dried and pelleted fertilisers derived from livestock manure, crop residue based digestate and ammonium nitrate applied to 2 fields of cereal crops (Burak & Sakrabani, 2023). The results showed that the yields from the novel fertilisers were comparable to those from mineral fertilisers. There was no significant impact of fertiliser treatment on root development, soil organic carbon, microbial biomass, pH or residual nutrient concentrations. However, the study was for a single harvest year and changes in soil quality are very unlikely to be apparent over such a short time scale.

Organo-mineral fertilisers may also contain contaminants (e.g. plastics, organic chemicals, PTEs, antibiotic residues etc) at concentrations that vary according to the source materials and method of production. Some useful studies on this topic have been published recently including as review of challenges and opportunities associated with biosolids-derived fertilisers (Marchuk *et al*., 2023) and a review of organic contaminants in fertilising products and their component materials (Faber & Montforts*,* 2022).

Summary of relevant legislation and government schemes (England)

- Maximum permitted levels of cadmium and some other PTEs (Cr, Hg, Ni, Pb, As) in organo mineral fertilisers will be controlled by the **EU Fertiliser Regulations (2019)**, which have been adopted in England.

Summary of voluntary schemes, initiatives and advice (England)

- None identified

5.7.2. Biochar.

Brief evidence review

The use of biochar was suggested as a core regenerative agriculture practice by Giller *et al*. (2021). There is a very large and growing body of research on biochar use in agriculture which it is beyond the scope of this study to assess in detail. However, a recent review by Hou (2021) on biochar for sustainable soil management summarised recent research where biochar has been used for:

- Soil PTE remediation
- Improving nutrient management
- Improving soil quality (e.g. improved aggregate distribution and water holding capacity; reduced compaction, erosion and runoff)
- Increasing soil organic C content and reducing GHG emissions

The author was careful to stress that despite these apparent beneficial effects, application of biochar in the field is still limited and many challenges remain before it is widely used and accepted. In the UK, the UKRI Biochar Demonstrator was set up to address uncertainties around biochar use in a UK context. Trial sites in the Midlands and Wales have been established to investigate the effects of biochar additions and identify the quantity of biochar required to maximise carbon sequestration and improve soil fertility (https://biochardemonstrator.ac.uk/).

Summary of relevant legislation and government schemes (England)

- Fertilising products containing or consisting of biochar are covered by the **EU Fertiliser Regulations** (EC, 2019) which limit concentrations of certain contaminants.

Biochar can currently only be applied to land under an exemption from the **Waste Management (England and Wales) Regulations 2006** (SI, 2006). The Environment Agency Low Risk Waste Position (LRWP) 60 (LRWP 60) stipulates the feedstocks which can be used to produce biochar for land spreading without an Environmental Permit (untreated wood and vegetable wastes) and LRWP 61 sets out rules for storing and applying biochar to benefit land (1 t/ha/yr application limit from permitted feedstocks).

Summary of voluntary schemes and initiatives (England)

- **Soil Association** organic standards state that only biochar from plant materials can be used and limit the PAH content.

5.7.3. Soil microbial inoculants.

Brief evidence review

Microbial inoculants consist of mixtures of bacteria and fungi (and, more rarely other microorganisms) that are introduced into an environment to perform a specific function such as biocontrol or plant growth promotion. Products currently on the market include biofertilizers, biopesticides and a wide range of other products with less defined characteristics, such as general plant growth promotion. The use of soil microbial inoculants was proposed by Giller *et al.* (2021) as a core regenerative agriculture practice.

In their review of soil microbial inoculants for sustainable agriculture O'Callaghan *et al.* (2022) reported that these products could improve soil quality and crop production through:

- Enhancing N fixation
- Solubilising phosphorus (P)
- Plant growth promotion and protection against soil-borne diseases
- Managing soil-dwelling invertebrate pests
- Improving plant stress tolerance (to drought, salinity and PTE toxicity)
- Bioremediation of PTE and other soil contaminants
- GHG mitigation
- Enhancing soil structure

However, the authors warn that "extensive and rigorous field evaluation of inoculants under a range of soil and environmental conditions has rarely been undertaken and is urgently needed to validate emerging inoculant products and underpin successful implementation by growers, especially in a market that is largely unregulated at present". Much more research is required before any of these products could be recommended as a reliable method for SSM.

Summary of relevant legislation and government schemes (England)

- Microbial biostimulants are covered by the **EU Fertiliser Regulations (2019)**

Summary of voluntary schemes, initiatives and advice (England)

- None identified

5.7.4. Rock dust

Brief evidence review

Rock dust is finely ground rock which when applied to soils is claimed to produce a number of benefits including improved crop production and soil health, and accelerated carbon capture (New Scientist, 2024; Rothamsted Research, 2023). A review of research into silicate rock powders (SRP) as an agricultural soil amendment (Swoboda *et al*., 2022) reported that rocks containing fast weathering minerals such feldspathoids or glauconites, and multi-nutrient mafic−/ultramafic rocks like basalt were most suitable for agricultural use. Overall, the research suggested that whilst SRPs may be effective as a soil amendment for strongly weathered tropical soils which are deficient in potassium, silicon and micro-nutrient, studies on soils in temperate regions were inconclusive. Findings from the 'Rock on Soils' project (led by JHI and SOPA) suggested that 3 years after treatment with a single application of crushed basic silicate rock, the soil at a farm in Scotland had a more balanced and higher value microbial biodiversity i.e. it was more 'biologically sustainable', containing more microbial species that sequester carbon and by inference improving the carbon storage capacity of the soil. However, there were no differences in soil structure, pH, CO_2 respiration rates, soil inorganic carbon or PTE concentrations (Rock on Soils Final Report, 2021).

Currently a 5-year BBSRC funded study (Enhanced Rock Weathering – Greenhouse Gas Removal ERW-GGR Demonstrator Programme) is investigating the potential for using crushed silicate rock on farmland to remove CO_2 from the atmosphere and improve UK food and soil security. There are 3 field sites (in mid-Wales, Devon and Hertfordshire) where measurements will be made of how effective crushed basalt is at removing CO_2, how downstream water alkalinity is affected, the benefits for on-farm productivity and soil quality, and potential accumulation of PTE in soils and plants (https://www.sheffield.ac.uk/uk-enhanced-weathering).

Summary of relevant legislation and government schemes (England)

- None identified

Summary of voluntary schemes, initiatives and advice (England)

- None identified

5.7.5. Paludiculture

The term paludiculture refers to farming on rewetted peat; in the context of lowland peat soils, it is most usually achieved through raising of the water table to achieve wetland conditions (e.g. by removing or blocking drains – see Section 5.5.7). It is claimed to offer a potential solution for maintaining the profitable use of lowland peatland whilst significantly reducing the GHG emissions associated with their current (dryland) agricultural use. (NE, 2022), and was identified as a potential SSM by some German farmers (Strauss *et al*., 2023).

A recent Defra-funded research project has looked in some detail at the potential for paludiculture in England (Mullholland *et al.,* 2020). The authors found that there were significant practical, economic and societal challenges for largescale implementation and concluded that "*As yet, paludiculture does not offer a comprehensive economic, large-scale, immediately implementable solution to the challenge of high GHG emissions from cultivated lowland peats, and other forms of emissions mitigation such as high-water level management of conventional agricultural land are likely to be needed. However, with further development of crops, water management systems and markets, paludiculture has the potential to make a valuable contribution to the development of more sustainable and resilient peatland farming systems in future, and to contribute to delivering the UK's net zero emissions target*."

Summary of relevant legislation and schemes (England)

- A **Paludiculture Exploration Fund** (PEF) is a grant scheme managed and delivered by Natural England to support projects to explore how paludiculture might be implemented in an English context.

Summary of voluntary schemes, initiatives and advice (England)

- None identified

5.8. Climate change and SSM

Climate regulation is one of the key ecosystem services delivered by agricultural soils and many studies have been published on the complex interactions between soils, their management and the potential impacts on the climate (e.g. Soil Use in Management Special Issue – 'Soils and Climate Change' February 2021 contained 22 papers on the subject). Soils are the largest terrestrial carbon (C) store and can be both a source and sink of greenhouse gases, depending on management (Hou, 2021). Increasing soil C through SSM has the potential to mitigate against climate change (Smith, 2021, BSSS 2021), and the improvements in soil quality associated with increased soil C can also contribute to climate change adaptation (BSSS, 2021). However, practices which aim to increase soil C may also increase soil N with the potential for increased nitrous oxide emissions; it is therefore important that SSM measures are implemented in a way that reduces the risk of increased GHG emissions.

The literature searches (Section 2.1) identified some useful papers on the relationship between SSM and climate change including the study by Amelung *et al*. (2020) who offered a global analysis of how sustainable soil C sequestration practices could contribute to climate change mitigation. They concluded that the greatest potential for C sequestration was in cropland soils, especially those with large yield gaps and/or large historic SOM losses. However, they also stressed that any measures adopted to encourage C sequestration must reflect local soil conditions and management opportunities. A team of European researchers (Keestra *et al*., 2023) thought that research was the key to supporting climate-smart SSM, and recommended that studies should focus on long-term interdisciplinary and multi-scale projects which include investigations of trade-off and the socio-economic factors affecting uptake.

Climate change is likely to have important implications for soils in the UK (see Gregory *et al*., 2015 for a good summary) and hence the suite of SSM measures which can and should be encouraged. In particular, changes in the quantity and distribution of rainfall and the effect of changes in temperatures are likely to affect the length of the growing season and hence will influence the practices that can be practically implemented. The Defra evidence review on sustainable soil practices, Smith *et al*. (2015) asked how climate change might affect the choice of soil management measures to achieve sustainability. From their review of the literature available at the time they concluded that "*adaptation strategies that increase the resistance and resilience of agricultural soils* [to climate change]*, such as maintaining field drainage systems on slowly permeable soils, growing cover crops, applying bulky organic manures and avoiding soil compaction also generally help improve farm profitability and should be encouraged through policy*." More recently, McGuire *et al* (2021) discussed how improving soil management in the UK could influence climate change mitigation (and agri-food productivity). Soil management practices which were assessed to make a significant improvement to climate change mitigation were MRV (measuring, reporting and verification procedures), reduced tillage, N_2-fixing legumes, multispecies swards, peatland restoration and organic fertiliser application. Measures thought to lead to minor improvements were improved timing and placement of fertiliser applications and grazing land management. Other soil threats and SSM measures which may become increasingly important in a changing English climate include:

Water erosion. Extremes of weather, including more intense rainfall/storm events will lead to a greater risk of soil erosion by water, sediment and nutrient loss to watercourses and flooding. Some of the physical SSM measures identified in Section 5.5 that act to mitigate erosion losses (e.g. maintain drains, cross slope barriers, buffer strips) and keeping soils covered all year round (e.g. cover crops), will become even more important in future.

Wind erosion. Where land is exposed to the wind there is an increased chance of soil erosion especially on peaty or sandy soils. In the drier conditions that may arise in future in some parts of England, SSM measures to minimise soil loss from wind erosion may need to be more widely implemented. Such measures could include cultivation perpendicular to wind direction (see for example, Strauss *et al.,* 2023), ensuring livestock such as pigs are located in low soil erosion risk zones (see Section 5.3.9), introduction/maintenance of hedgerows and tree belts (see Section 5.5.4), and planting cover crops and other practices which minimise the time the soil surface is left bare (see Section 5.3.1).

Irrigation. Drier and/or hotter summers and irregular rainfall patterns will increase importance of SSM measures related to irrigation management. The UK Irrigation Association (UKIA) has produced an irrigation water strategy for UK agriculture and horticulture (Knox *et al*. 2020), and this notes that there would be an increased risk of soil erosion from more intensive irrigation, highlighting the conflicting interests of the environment versus irrigated agriculture. Advice for farmers and growers on irrigation and climate change is available from the UKIA.

Diverse rotations/swards. As climate change continues, adopting diverse rotations with more legumes may provide greater resilience in arable systems (see Section 5.3.4), whilst using diverse, multi-species swards may do the same for grasslands, although presently the evidence on the effects on soils is lacking (see Section 5.2.4). Choosing appropriate crops or plant species that are more resilient to climate stresses such as drought will also be crucial to maintaining productivity.

Agroforestry. Pantera *et al* (2021) identified several sources of information on the impact of agroforestry on biodiversity and on climate change mitigation. In summary, trees can modify environmental conditions (e.g., radiation, temperature, and humidity), creating microhabitats for different species, therefore increasing biodiversity. There is also evidence that agroforestry can a) reduce temperature variations by providing shade (b) act as a barrier to reduce wind speeds, and (c) reduce the effects of catastrophic events such as flooding (better soil structure provided by tree roots can enhance water infiltration and reduce runoff). In addition, climate change mitigation is provided via C sequestration in the subsoil and reductions in GHG exchange during hot periods.

In summary, any individual SSM measures that act to build, maintain or protect SOM will be important in improving the physical, chemical and biological quality of the soils and hence will provide soil with a degree of resilience to a range of climate stresses. Thus, under future climate change scenarios it will become even more important to encourage the uptake of SSM measures such as the application of bulky organic materials, returning crop residues and cover cropping. Predicted increases in the amount and intensity of rainfall events will mean that measures to control erosion and associated nutrient losses will also become more important. In Scotland, a report by Lilly *et al*. (2018) concluded that more information was needed on the interaction between climate and soil compaction and erosion risks, but that the erratic weather patterns associated with a changing climate together with changes in machinery and farming practices would increase the susceptibility of Scottish soils to erosion or compaction damage. Development of avoidance and mitigation strategies requires an integrated approach encompassing the multiple factors contributing to erosion and compaction risk. However, a team led by Lancaster University (Ockenden *et al.*, 2017) warned that some SSM actions (in this case, reducing P inputs to deliver sustainable water quality under climate change scenarios) might not be compatible with the need to maintain agricultural productivity, and stressed that interactions between climate and agro-ecosystems are highly non-linear and changes to either will have feedback effects on the other.

5.9 Land use practices, agricultural systems and SSM

There is a wide spectrum of land use practices and agricultural systems under which land in England can be managed and from which food can be produced (and other ecosystem services provided). These range from intensive chemical-based systems at one extreme through to a variety of lower intensity agroecological systems including regenerative farming and rewilding (where food may still be produced). The SSM practices discussed above are "bundled" in various ways and to a greater or lesser extent in these different systems.

As stated previously, it was not the objective of this study to examine these broad approaches to farming, although it was possible to identify various SSM measures that may need to be adopted as part of certification schemes e.g. organic/biodynamic certification (see Section 6.2). However, it is interesting that Burgess *et al* (2023) in their evaluation of agroecological and regenerative farming in the UK found broad differences in the underlying philosophies of the systems, *viz*:

- organic farming places strong restrictions on inputs,
- agroecological farming analyses often focus on principles (e.g. social justice, economic and political aspects)
- regenerative farming typically emphasises the enhancement of soil health and biodiversity at a farm-scale.

The authors also noted that the terms regenerative agriculture and agroecology may be employed interchangeably, sequentially (i.e. regenerative practices are seen as steps towards a bigger whole-farm agroecological system) or discretely. From this analysis, it is regenerative farming that seems to place the most emphasis on soil health, although clearly the Soil Association aims to ensure that organic farmers sustain the health of soils (as well as ecosystems, animals and people).

6 LEGISLATION AND VOLUNTARY SCHEMES

6.1. Legislation mapping

The list of potentially relevant regulations, developed in consultation with ADAS soil scientists, relevant stakeholders and the OEP project team, comprised:

- The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018 (Farming Rules for Water)
- The Fertiliser Regulations 1991, EC 2006, and EC 2019.
- Nitrate Pollution Prevention Regulations 2015 and the Nitrate Pollution Prevention (Amendment) Regulations 2016
- Plant Protection Product Regulations EC 1107/2009
- The Sludge (Use in Agriculture) Regulations 1989
- Code of Practice for the Agriculture Use of Sewage Sludge 1996
- Water Resources Act 1991
- The Water Environment (Water Framework Directive) (England and Wales) Regulations 2017
- The Waste Management (England and Wales) Regulations 2006
- Environmental Permitting Regulations (England and Wales) 2016
- Climate Change Act 2008
- Environmental Act 2021
- The Environmental Protection Act 1990
- Agriculture Act 2020

Other specific pieces of legislation and standards were also included in the mapping where appropriate (e.g. the Pesticide Regulations; British Standards for compost and digestate PAS100/110).

The government voluntary grant schemes considered were the SFI and Countryside Stewardship (CS). These both include actions which could incentivise farmers to consider one or several SSM measures. In addition, the following non-government voluntary schemes were examined:

- Biodynamic Certification
- Certified Regenerative (A Greener World)
- Fair to Nature (RSPB)
- LEAF Marque
- Pasture for Life (Pasture Fed Livestock Association – PFLA)
- Red Tractor
- Regenagri
- Soil Association Organic Standards for GB
- Biosolids Assurance Scheme (BAS)

The Catchment Sensitive Farming (CSF) advice programme was not specifically addressed in the mapping exercise because it is not linked to individual soil management practices but is focussed on providing location specific advice and is primarily driven by the aim of improving water quality in the local catchment. However, it was considered as a potential model for the delivery of advice and education (See Section 5.6.3). Carbon credit schemes (e.g. Agreena, Indigo, Farm Carbon Toolkit, Soil Capital) were not considered to be within the scope of this study. Whilst many of the measures these schemes advocate do link to some of the SSM measures identified here and will therefore indirectly incentivise SSM, their primary objective is to provide credits for carbon reductions and climate friendly farming practices rather than to protect soils from the threats they face or improve soil quality and health *per se.*

Table 11. Mapping of SSM measures to regulations or voluntary schemes which either directly or indirectly promote, control or advise on the measure (see text in Section 5 for more details of how each SSM measure is addressed)

Category	SSM measure	Number of regulations addressing the measure	Addressed by government voluntary grant schemes (Y/N)	Number of private voluntary schemes or initiatives addressing the measure
Soil inputs	Apply organic materials	5	Y	7
	Optimise OM applications	2	Y	5
	Apply lime	1	N	2
	Apply gypsum	1	N	2
	Apply (organic material) mulch	1	Y	1
	Return straw/crop residues	0	N	1
	Optimise irrigation practices	2	N	4
	Optimise agrochemical use	1	Y	7
	Optimise mineral fertiliser use	3	Y	6
Grass and grazing management	Extensive grazing	0	Y	0
	Rotational grazing or similar	0	Y	1
	Manage grazing season length etc	1	Y	5
	Multi species/diverse swards	0	Y	2
	Regular re-seeding	0	N	1
	Silvopasture/agroforestry	0	Y	2
Crops and rotations	Cover crops/green manures	1	Y	4
	Overwinter stubble	1	Y	1
	Early establish winter crops	1	N	1
	Diverse rotations	0	N	4
	Leys/rotational grass	0	Y	1
	Fallow	0	Y	1
	Intercropping/companion crops	0	Y	3
	Under sowing	1	Y	1
	Integrated livestock	0	N	2
	Short rotation coppice/biomass	0	N	1
	Reversion to grassland	0	Y	1
Mechanical pressure	No tillage; min/reduced tillage	0	N	2
	Reduce soil loads	0	Y	1
	Control trafficking	1	Y	0
	Reduce plough frequency/depth	1	N	0
	Cultivate/loosen compacted soil	1	Y	2
	Leave autumn seedbeds rough	1	N	0
	Avoid harvest on wet soils	1	N	0
Physical environment	Adapt ploughing to topography	1	N	1
	Cross slope barriers/beetle banks	0	Y	1
	Field or riparian buffer strips	1	Y	4
	Introduce trees/hedges	1	Y	5
	Set aside of marginal land	0	Y	0
	Appropriate drainage	1	Y	1
	Hard tracks for stock movement	1	Y	2
Other	Local soil monitoring and testing	1	Y	6

Key:

Number of regulations or schemes. 7+ ▇ 5-6 ▇ 3-4 ▇ 1-2 ▇ None ☐

Addressed by government voluntary grant schemes: Yes ▇ No ☐

The legislation mapping provided a framework whereby the regulation and voluntary schemes could be mapped against the identified SSM measures. This allowed a clearer picture to be developed of where there are gaps in the existing set of regulations and schemes pertaining to specific SSM measures or broad categories of SSM measures (Table 11).

6.2. Scope and efficacy of regulations and voluntary schemes in England

6.2.1. Regulations and government schemes

Table 11 indicates that there is a strong regulatory focus on SSM measures related to soil inputs. Regulations addressing soil inputs such as the Sludge (Use in Agriculture) Regulations 1989 (SI, 1989) and the Fertilizer Regulations (EC, 2019) specifically aim to reduce the risk of soil contamination (e.g. from pathogens, PTEs or organic chemical contaminants) where non-farm organic materials such as biosolids, compost and digestates or mineral/manufactured fertiliser products are applied. There is little focus on other aspects of soil protection such as reducing the threat of soil loss, compaction or erosion.

Other regulatory controls on soil inputs are specified in the FRfW (SI, 2018) and the Nitrate Pollution Prevention Regulations (SI, 2015, 2016). Whilst these regulations make reference to many of the SSM measures identified, they are not primarily targeted at promoting SSM *per se.* Instead, they focus on the protection of watercourses from diffuse nutrient and sediment pollution, although they often aim to achieve this by requiring best practice when working with soils (i.e. they require farmers to adopt management practices that reduce the risk of soil compaction and erosion). In addition, some of the restrictions imposed in the regulations could indirectly influence SSM by reducing nutrient losses and hence enhancing soil fertility and productivity.

It is difficult to locate any published literature on the success or otherwise of these regulations with respect to encouraging or achieving SSM except in relation to soil PTE contamination. The Sludge (Use In Agriculture) Regulations (SI, 1989) set statutory maximum limits for the total concentrations of Cd, Cu, Pb, Hg, Ni and Zn permitted in sludge amended soils, as these are considered to pose the greatest risk to soil and human health. Additionally, the Sludge Regulations also contain maximum annual PTE addition rates averaged over a 10-year period, to ensure the loadings of PTEs are not elevated. In 1996, the UK Department of Environment issued a 'Code of Practice' containing advisory maximum permissible soil PTE concentrations and average annual PTE addition rates (DoE, 1996). Following implementation of the Sludge Regulations, two independent scientific reviews were conducted to determine possible risks to food safety, assess the potential long-term impacts of repeated sludge application to agricultural land, and confirm that the legislation put in place was sufficient to protect soil quality (MAFF/DoE, 1993). It was concluded that PTE uptake by plants was unlikely to pose a significant risk to food safety, hence the limits proposed by the Sludge Regulations (SI, 1989) were deemed sufficient to protect plants, animals, and humans from PTE toxicity, although the same could not be said for soil microorganisms. As a result, the Long-term Sludge Experiments (LtSE) were established in 1994 to determine the effects on soil fertility and microbial activity of PTEs contained in biosolids applied to agricultural soils (Gibbs *et al.,* 2006 a,b). Overall, there was no evidence that the PTE applications were damaging soil microbial activity in the short term after the cessation of sludge cake addition. However, in a recent meta-analysis using data from the LtSE by Charlton *et al* (2016) it was found that there had been significant decreases in biomass C in soils where the total concentrations of Zn and Cu were below the current UK statutory limits. In a parallel study, Charlton *et al.* (2016b) reported a decrease in Rhizobium MPN (most probable number) in treatments with Zn, whilst no significant effect was noted with Cu. In contrast application of biosolids predominantly contaminated with Cd appeared to have no effect on biomass C and Rhizobium MPN at concentrations below the current UK statutory limit.

A certain amount of debate has arisen around the efficacy of the EC Fertiliser Regulations (EC, 2019). New evidence on the adverse effects of Cd accumulation linked to fertilizers and the absence of harmonized limits among European Member States (MS) led the EU to revise the previous regulations by introducing a lower limit for Cd and guarantee a high level of soil protection (Ulrich, 2019). However, in their recent risk assessment of contaminants in fertilisers for DG Environment, Deleebeeck *et al*. (2021) concluded that with a concentration limit of 60 mg Cd/kg P_2O_5 there may still be a risk to soils following long-term use of high-Cd mineral P fertilisers and for people with high vegetable consumption. They noted that there are still uncertainties which may impact the outcome of risk assessments, such as leaching of Cd to deeper soil layers, and pointed out that regional differences in soil characteristics and background Cd concentrations should be accounted for when setting limit values or adopting other regulatory measures for Cd in fertilisers.

The other categories of SSM measures (i.e. grass and grazing management, crop and rotations, physical environment, mechanical pressures) are not well addressed in the current regulatory framework, although the FRfW (SI, 2018) do require land managers to take “reasonable precautions” to prevent agricultural diffuse pollution resulting from land management and cultivation practices on agricultural land; these could include SSM measures such as undersowing or sowing a cover crop to stabilise the soil after harvest. Part of the reason for the lack of regulation is that many SSM practices are very dependent on the local context making it almost impossible to legislate. For example, it may not be practically or economically feasible to adopt particular cultivation or grazing practices on certain soil types or under certain weather conditions, or due to other factors outside the control of the farmer or land manager. Instead, these SSM practices are encouraged under the umbrella of government-backed voluntary schemes (i.e. SFI and Countryside Stewardship, Table 11). The purpose of these schemes is to incentivise farmers to “adopt and maintain sustainable farming practices that can protect and improve the environment” (Baker, 2023). Again, the primary focus of these schemes tends not to be on soils, although the SFI supports farmers to assess and improve soil quality including measuring SOM content (SAM1), establishing soil cover over winter (SAM2) which will protect soils and reduce erosion risk and using herbal leys in arable systems (SAM3) which will enhance SOM.

Very little information was identified in the literature on the uptake or success of these voluntary schemes in promoting SSM. Hejnowicz *et al* (2016) conducted an online survey to explore farmers perspectives of Natural England’s Environmental Stewardship programme (the predecessor to Countryside Stewardship). Respondents were asked to identify the environmental objectives most frequently met by the agreements they had been involved with. They found that around 49% of respondents indicated the schemes they were involved with met natural resource conservation objectives (particularly in relation to soil), but no information was obtained on how soils might have been affected by the scheme. A survey undertaken in 2017-18 aimed to establish a baseline condition for the Countryside Stewardship (launched in 2015), with soil quality assessed in relation to resource protection options. At both arable and grassland sites there were very few differences in soil physical and chemical properties between areas in or outside Countryside Stewardship options, probably because many of the Countryside Stewardship options will have been newly established. There was some indication that topsoils under arable Countryside Stewardship options had lower porosity than soil managed outside Countryside Stewardship, but differences were small and probably not significant in functional terms. Importantly, the differences in some soil properties (e.g. SOC and visual evaluation scores) between soil types (seasonally waterlogged and freely draining) were greater than any differences between land managed in or outside Countryside Stewardship option. Nevertheless, the authors concluded that the soil quality measurements provided a robust baseline from which changes over time can be measured (Jones *et al.*, 2019). In future, soils data from monitoring programmes such as the England Ecosystem Survey (EES) will help in evaluating the impacts and success of national schemes such as the SFI.

6.2.2. Private voluntary schemes

Tables 11 and 12 highlight the importance of private voluntary schemes (e.g. Soil Association Organic Standards, Regenagri, Biodynamic Certification etc.) in encouraging SSM practices which cannot always be dealt with effectively by legislation

Table 12. Mapping of SSM measures to private voluntary schemes which either directly or indirectly promote, control or advise on the measure (see text in Section 5 for more details of how each SSM measure is addressed)

Category	SSM measure	Soil Assoc.	Bio dynamic Cert.	Cert. Regen./ Regenagri	Red Tractor	Pasture for life	Fair to Nature	LEAF
Soil inputs	Apply organic materials	Y	Y	Y		Y		
	Optimise OM applications	Y	Y			Y		Y
	Apply lime	Y	Y					
	Apply gypsum	Y	Y					
	Apply (organic material) mulch			Y				
	Return straw/crop residues			Y				
	Optimise irrigation practices	Y		Y				Y
	Optimise agrochemical use	Y	Y	Y		Y	Y	Y
	Optimise mineral fertiliser use	Y		Y		Y	Y	Y
Grass and grazing management	Extensive grazing							
	Rotational grazing or similar			Y				
	Manage grazing season etc	Y	Y	Y		Y		Y
	Multi species/diverse swards			Y		Y		
	Regular re-seeding					Y		
	Silvopasture/agroforestry	Y		Y				
Crops and rotations	Cover crops/green manures	Y	Y	Y			Y	
	Overwinter stubble						Y	
	Early establish winter crops						Y	
	Diverse rotations	Y	Y	Y				Y
	Leys/rotational grass						Y	
	Fallow			Y				
	Intercropping/companion crops	Y	Y	Y				
	Under sowing	Y						
	Integrated livestock				Y	Y		
	Short rotation coppice/biomass			Y				
	Reversion to grassland			Y				
Mechanical pressure	No tillage; min/reduced tillage	Y		Y				
	Reduce soil loads							
	Control trafficking							
	Reduce plough frequency/depth							
	Cultivate/loosen compacted soil	Y						Y
	Leave autumn seedbeds rough							
	Avoid harvest on wet soils							
Physical environment	Adapt ploughing to topography	Y						
	Cross slope barriers/beetle banks			Y				
	Field or riparian buffer strips	Y		Y		Y		
	Introduce trees/hedges	Y	Y	Y		Y		Y
	Set aside of marginal land							
	Appropriate drainage							Y
	Hard tracks for stock movement	Y						Y
Other	Local soil monitoring and testing	Y		Y		Y	Y	Y

Table 12 illustrates the more comprehensive encouragement of SSM measures by The Soil Association (Organic Certification) and the regenerative farming schemes (Regenagri and Certified Regenerative). Interestingly none of the voluntary schemes place much emphasis on SSM measure targeted at alleviating mechanical pressures on soil, presumably because these are so context specific (see Section 6.2.1 above).

The literature searches only identified two schemes which had been evaluated in terms of their efficacy with respect to SSM; these were the LEAF Marque scheme and the Pasture Fed Livestock Association (PFLA). Reed *et al* (2017) interviewed 37 farmers who were participants in the LEAF Marque scheme. In relation to soil management and fertility, 64% of participants agreed that since becoming LEAF Marque certified the condition of their soil had improved. All LEAF Marque certified businesses who regularly tested SOM saw improvements and almost all participants observed improvements in the condition of the soil and the life within it, either through formal testing and experimental work in collaboration with research organisations, or through counting earthworms. Norton *et al* (2022) collected data from 50 PFLA farms representing a broad range of soil types and locations, including a variety of enterprise mixes and farmers with differing levels of expertise and experience in PFLA approaches. They found many of those who had been members of PFLA for longest tended to have higher levels of soil carbon, although no other differences in other soil properties (bulk density, total N, pH, total and Olsen P) were reported.

6.2.3. Monitoring and enforcement

Compliance with Regulations such as the FRfW (SI, 2018) the Nitrate Pollution Prevention Regulations (SI, 2015) and the Sludge (Use in Agriculture) Regulations 1989 (SI, 1989) is mandated by law, and is assessed by the Environment Agency (EA). For example, EA agricultural regulatory inspection officers assess compliance with the FRfW during farm inspections, checking if farmers are complying with the eight specific rules related to water management. These rules cover areas such as planning manure and fertiliser use, storing organic manures, applying manures or fertilisers, preventing soil erosion, and protecting against soil erosion by livestock. Compliance can be demonstrated by producing a nutrient management plan or other written plan. Land managers must take all appropriate reasonable precautions to help mitigate against the risk of diffuse agricultural pollution, unless there are appropriate agronomic or environmental reasons not to.

Defra check compliance with government voluntary schemes such as the SFI using a variety of methods including administrative checks, site visits, remote monitoring technology, evidence checks (e.g. soil management plans, SOM test results etc.) and via the annual declaration (https://www.gov.uk/guidance/checking-youre-complying-with-your-sfi-agreement). This work is typically carried out by the Rural Payments Agency (RPA).

Private voluntary schemes will each have their own standards and guidelines that farmers and growers are required to comply with in order to receive certification under the scheme, and their own methods for monitoring compliance. For example, the Soil Association publish a detailed set of organic certification requirements, with inspections carried out by their subsidiary, Soil Association Certification. Similarly, Regenagri publishes various sets of standards for different producers; the supporting data required to comply with these standards must be certified by certification bodies holding external accreditation. Some of the scheme requirements can be quite non-specific in terms of actions that are required. For instance the Soil Association requires that the soil is managed "to enhance stability, soil organic matter levels and soil structure and to prevent compaction, erosion and run-off", but only brief guidance is given on how this is to be achieved and which soil management practices would demonstrate compliance (Soil Association Standard GB 2.4 'Managing your soil'; https://www.soilassociation.org/media/25986/sa-gb-farming-growing.pdf).

6.3 The role of international policy

International and European soil policy may be expected to have an influence on policy and legislation in England, with much EU legislation (e.g. the EC Fertiliser Regulations; EC, 2019) retained on the statute books following exiting the EU. In 2006, the EU attempted to institute a Soils Framework Directive to address soil protection at the European level. This was unsuccessful due to strong resistance from 5 MS and was formally withdrawn in 2014. Marini *et al* (2020) suggested that this was because MS did not perceive soil management to be a "cross-border" issue (unlike air and water protection) therefore it was not necessary to address it at a supranational level. Soil protection has very often been perceived to be less important than the protection of water, air, biodiversity etc. A paper by researchers at the University of Exeter (Humphries & Brazier, 2018) claimed that the UK and EU both treated soil conservation as a secondary effect of actions taken to deal with other environmental objectives. Similarly, Marini *et al.* (2020) stated that even though there was not a "comprehensive" legislation scheme for soil, the areas which would have been covered by a Soils Framework have been addressed by "overlapping" legislation on fertiliser usage or environmental schemes. Thorsøe *et al.* (2019) commented that the Common Agricultural Policy (CAP) only included soil erosion control as a secondary objective, with a much greater level of importance placed on other environmental issues. Since these discussion papers were published, the EU has produced a 'Soil Strategy for 2030' setting out a framework of measures to 'protect and restore soils and ensure that they are used sustainably' https://environment.ec.europa.eu/topics/soil-and-land/soil-strategy_en. A recent outcome from this Strategy is the proposed introduction of a new 'Soil Monitoring and Resilience Directive' or 'Soil Monitoring Law'). This Directive is currently (July 2024) going through the European Parliament and will include measures for 'monitoring and assessing soil health, based on a common definition of what constitutes a healthy soil, for managing soils sustainably, and for tackling contaminated sites' Soil monitoring and resilience directive (europa.eu).

One effect of the previous absence of overarching soil legislation at the EU scale was a lack of consistency between the SSM measures adopted by different MS to account for local context and conditions (Turpin *et al*., 2017). This is also reflected in the very large number of potential and varied SSM measures identified in the literature (see Section 4). The European Court of Auditors (2023) drew some important conclusions from their audit of CAP measures and actions relevant to manure management in the Nitrates Directive (EC, 1991) to assess whether the EC and MS made effective use of EU tools for managing agricultural soils and manure sustainably. Amongst other findings they concluded that:

- The often "*unambitious definition and requirements*" of the standards and limited national targeting meant there was "*considerable scope to improve soil health*".
- MS requirements often necessitated only limited changes in farmers' behaviour and limited improvements to farming practices. The report concluded that the legislation assessed had "*a limited impact overall on sustainable soil and manure management*".

6.4 Summary

The fact that there are a whole range of regulations and schemes in England which are not specifically targeted at SSM but which affect or influence SSM to a greater or lesser extent perhaps reflects the lack of a coherent policy framework and overarching soil legislation in England. This is not an issue unique to this country. For example, Turpin *et al.* (2017) identified 410 different soil conservation measures in place across Europe, suggesting that few European countries have implemented overarching soil management legislation (see also Section 6.3). Some authors have questioned whether the role of legislation should be to regulate or support the implementation of SSM measures. For instance, Marini *et al*. (2020) commented that the EU Fertiliser Regulations are effective at limiting negative actions but should also "promote strategies for improving soil functions." Evidence from other countries reported by Hurley *et al.* (2023) indicates that transitions (in this case towards agroecological[9] and regenerative farming practices) can succeed where "the right combination of policy instruments (e.g. grants, support for advice and collaboration, cultural support) are sustained by long-term political will".

[9] Agroecology is the application of ecological principals to agricultural systems and practices, allowing food production and nature to co-exist. An example would be agroforestry.

7 BEST PRACTICE CASE STUDY SUMMARY

Interviews with 3 'best practice' case study farms were conducted in Spring 2024 to better understand how the regulation and governance supporting the sustainable management of soil operates in practice, and the implications it has for farming businesses. The selected farms covered a range of geographical areas, cropping systems and soil types:

- **Case Study 1.** A farming enterprise with 3 sites in Lincolnshire. Principally arable, although sheep graze cover crops and grass/herbal leys. Soils include light heathland soils, organic clay loams, sandy loams, silt loams and heavy clays.
- **Case Study 2.** A research and demonstration farm in Leicestershire. Mostly arable (cereal dominated), but uses neighbouring farmers' sheep to graze some permanent grassland, leys and cover crops. Heavy textured soils (silty clay loam/clay loams)
- **Case Study 3.** A mixed arable, beef and sheep farm in Norfolk that has recently transitioned to livestock only. All the farm is on rented land, highlighting some of the issues tenant farmers face. Soils are sandy loam/loamy sands over chalk, with a high pH (8).

Summary reports produced following the interviews with each of the best practice case study farms can be found in Appendix 4. The main findings are summarised below.

The case study farms had different understandings of SSM although all the definitions/meanings were very broad. They focussed more on the productivity/practical aspects rather than soil health/quality or environmental risks, unlike the definition proposed at the start of this study (see Section 3.4 and below).

- **Case Study 1:** '*Sustainable soil management is all about producing the best crops with the least amount of work to our soils'*
- **Case Study 2:** '*Sustainable soil management is about doing the right operation for the field and crop in question at the right time'*. They also commented that in the context of the SFI requirement to assess soil health and produce a soil management plan '*soil health can be whatever you want it to be*'.
- **Case Study 3:** '*Sustainable soil management is the fundamental crux of why we have changed everything on farm'*
- **This Report (Section 3.4):** '*The adoption of soil management practices that promote soil health/quality and/or minimise the threats to soils, whilst maintaining agricultural productivity and minimising the risks to the wider environment'*.

All the case study farms have experienced problems with soil compaction, with machinery weight mentioned as a specific issue. Other issues included limited working windows and waterlogging (due to an old drainage system and high rainfall) on heavier soils, and wind erosion on lighter soils. Case Studies 1 and 2 both produce a nutrient management plan (NMP), with Case Study 1 employing a software package to fulfil Red Tractor NMP and record keeping requirements. Case Study 3 (livestock only) has minimal nutrient inputs with no manufactured fertiliser N applied. All the case studies routinely sample their soils. Case Study 1 uses soil mapping for precision equipment and samples for SOM every 4 years. The SFI has encouraged increased in field assessments of soil condition, such as visual evaluation of soil structure (VESS), which is used to produce a soil management plan. Case Study 2 samples soils across the farm every 5 years (or more often), using visual soil assessment (no methodology specified) to guide cultivation choices. Case Study 3 samples for nutrient status and pH, stating that '*We keep a track of everything*'.

Their use of the following (sustainable) soil management practices was discussed with each case study:

- **Cultivations.** Neither of the arable farms has a fixed cultivation strategy, with both tailoring it to soil conditions. Case Study 1 has reduced the level of ploughing, motivated by a desire to improve their carbon footprint. No till (direct drilling) is conducted on some fields/farms, with discs/tine cultivators and subsoilers used according to soil conditions. In Case Study 2, one field is focused on conservation agriculture and has been no-till for over 14 years. On this field a 14% increase in topsoil SOM was measured in the first 10-years; annual ploughing of part of the field reduced this to pre-no till levels within 3 years; anecdotally, this field can be worked most quickly and travelled on the earliest. Case Study 3 tried zero-till when still an arable enterprise, but '*couldn't make it work'*.
- **Residue/stubble management.** Both arable farms return straw/crop residues, with Case Study 2 stating '*we want to leave as much residue as we can in the field to conserve and return organic matter to the soil'*
- **Grass leys.** All the Case Studies use leys. Studies. Case Study 1 uses them to 'rest' fields with heavier soils; and SFI options have led to a switch to herbal leys (from grass-clover). At Case Study 2, herbal leys (supported by the Countryside Stewardship GS4 option) are used to help control blackgrass and build fertility. Case Study 3 uses herbal leys under the SFI, including deep rooting species in dry seasons.
- **Livestock integration.** Both the arable farms use some form of livestock integration. At Case Study 1, sheep graze cover crops and some 2-year grass leys, whilst Case Study 2 uses neighbouring farmers' sheep to graze some permanent grassland, leys and cover crops. Case Study 3 used to have outdoor pigs but these caused soil structural damage.
- **Drainage.** Case Studies 1 and 2 have drainage systems on some or all their land and both take an active approach to their management.
- **Organic material (and other) applications.** At Case Study 1, solid & liquid digestates, poultry and pig manures are regularly applied for their nutrient value, with compost used to improve SOM levels. The FRfW motivated the business to invest in low emission spreading equipment for liquid manures. Case Study 2 has a 'straw for muck' deal where a neighbouring farmer provides cattle FYM; they have also experimented with 'novel' materials e.g. biochar and water pre-treatment waste. Fibrophos and gypsum have also been used to improve soil structure and tackle declining soil P. Case Study 3 is thinking about applying digestate (farm based) to 'kick start' forage production on newly established leys.
- **Cover cropping.** Both the arable farms use cover crops. At Case Study 1, the initial driver was to control erosion and retain N, but more recently it is to support sheep grazing and obtain SFI payments. They had little success with oversowing grass into maize and catch cropping after vining peas. Case Study 2 uses cover crops for ecological/environmental reasons rather than improving SOM; beetle banks and buffer strips are also used to improve biodiversity.
- **Grazing management.** Case Study 3 uses a grazing only system (no cutting) to keep grass cover long and moves animals daily, similar to 'mob-grazing' principles.

Each Case Study shared information on their motivations and incentives to adopt SSM practices.

- **Case Study 1**. Accreditation to schemes (e.g. Red Tractor, Leaf Marque) steered many decisions, but the SFI provided a more formal incentive. Carbon management and moving towards net zero played a part in stimulating a move away from the plough. They considered that best practice was more likely to be driven by financial considerations rather than legislation.

- **Case Study 2**. The primary motivation is a productive and profitable farming system, looking first for improvements in efficiency and second for environmental improvements. A key driver for adopting soil management practices is climate change, with the aim to build soil resilience by introducing practices to enhance SOM and improve soil structure. However, they are concerned that climate change is already sufficiently severe that it has '*wiped out efforts*' to improve soils, particularly this season (2023/24) where waterlogging of heavy clay soils led to flood barriers being washed away and '*earthworms drowned'*. Most of the Countryside Stewardship options included on farm are for ecological/biodiversity improvements rather than soils *per se*. Their current SFI application includes soil and nutrient management options, with SSM as one of the drivers, but 'cash flow' is probably the over-riding factor. SFI payments were considered too low to provide an incentive '*to go the extra mile'*.

- **Case Study 3**. The transition from arable to grass was driven by the small margins on the arable enterprise, particularly given the pressures faced by a tenant farmer needing to pay a landlord. They wanted to improve soils and reduce inputs (particularly agrochemicals) but were unable to do so without compromising yields. '*We tried reduced tillage and cover crops but struggled to make it work…. margins are limited for a tenant farmer'*. Both Countryside Stewardship and SFI were essential in enabling the transition from arable farming. The primary motivation for this farm was financial. *'There is no excuse for not doing the right thing if you are making money, however if you're not then it's difficult to think environmentally'.*

Overall all three case studies recognized the need (and strongly desired) to maintain and improve soil quality/health and minimise environmental impacts, and had adopted many of the SSM practices outlined in this review in order to try to achieve this. However, the over-riding and primary driver for all decisions on farm was financial, with SFI and CS payments seen as essential (although potentially inadequate) to support SSM.

8 STRENGTHS AND WEAKNESSES IN THE REGULATORY FRAMEWORK FOR THE SUSTAINABLE MANAGEMENT OF SOILS

One of the main objectives of this project was to make an assessment of the strengths and weaknesses in government's regulatory/governance framework for the sustainable management of soils, and to assess the role played by alternative non-regulatory measures such as government funded grant schemes (SFI and Country Stewardship) or via private voluntary schemes (e.g. the Soil Association; Pasture Fed Livestock) in encouraging the uptake of SSM in England.

A SWOT (Strengths, Weaknesses, Opportunities, Threats) approach was adopted and used to draw together the various information elucidated in the literature reviews on SSM practices and measures (Sections 4 and 5) and the efficacy and extent of adoption of the various regulatory and voluntary schemes (Section 6). The outcome of the SWOT analysis for the various categories of SSM measures is summarised in the tables on the following pages (Tables 13-18) and has been used to inform the final report summary and recommendations (Section 8).

Table 13: Strengths, weaknesses, opportunities and challenges (SWOT) in the regulatory framework for SSM measures related to <u>soil inputs</u>

Strengths	**Weaknesses**
• Although the regulations (Nitrate Pollution Prevention Regulations (SI, 2015;2016)/FRfW (SI, 2018)) are mainly targeted at reducing nutrient losses to water, they will have some benefits to soil nutrient management. The Fertiliser (EC, 2019) and Sludge Use in Agriculture Regulations (SI, 1989) aim to minimise soil contamination risks. • Voluntary schemes (e.g. Biosolids Assurance Scheme, Biofertiliser Certification scheme) also encourage compliance with the regulations and help facilitate best practice, minimise risks, and create a level of familiarity with the practices. • Organic materials should reduce fertiliser costs, whilst ensuring optimum nutrient supply will maximise profit. OM additions will maintain and improve soil quality and sustain crop yields. • The guidance supporting the use of organic materials is underpinned by a robust and comprehensive scientific evidence base. • Stakeholder analysis in Germany, reported that the use of organic fertilisers was one of the top seven SSM practices (Strauss *et al*, 2023).	• There is a risk that measures introduced to reduce losses to the environment by one pathway (e.g. moving manure applications from autumn to spring to reduce nitrate losses to water) may result in increased losses via another pathway (e.g. ammonia emissions to air or phosphate losses to water) or result in soil damage e.g. from compaction. • There is a risk of diffuse and point source water pollution from the storage and application of organic materials (these risks can be minimised by complying with current legislation). • Implementing regulations can be difficult due to the lack of trained regulators and the need for comprehensive records to demonstrate compliance. • Perception issues may affect usage of some organic materials e.g. plastics in biosolids/compost; odours (Case *et al,* 2017). • The cost of compliance can be high. There may be a requirement for additional storage capacity or specialised spreading equipment.
Opportunities	**Threats**
• Education and guidance are required to both ensure best practise and to enable a better understanding of wider benefits, and to contextualise perceived risks. • Improved nutrient management especially of organic materials has the potential to reduce nutrient surpluses which will benefit the wider environment (i.e. reduced nutrient losses to water and nitrous oxide emissions to air) • Reducing the need for manufactured fertilisers will reduce agriculture's overall carbon footprint because of the savings in GHG emissions from fertiliser production. • Under future climate change scenarios, soil inputs which build or maintain SOM levels will become increasingly important; soils with high SOM have better fertility, structure and stability, providing protection against an increased level of threats (e.g. from erosion).	• There are alternative markets for some organic materials (e.g. poultry manure and straw can be used for power) which may limit availability. • Investment in farm infrastructure (e.g. increased slurry storage and precision application equipment) may be required to ensure manure applications are made when soil and weather conditions are appropriate. • For 'non-agriculturally' sourced organic materials e.g. biosolids, compost and anaerobic digestate there are concerns regarding microbial contaminants and the risks to soils and the wider environment from potential hazards such as microplastics, organic chemical contaminants etc. Some markets will not accept crops where biosolids or digestate have been applied. • Enforcement of legislation is not guaranteed, and self-enforcement is hard to prove (e.g. self-reported high compliance rates with the closed fertiliser spreading periods; Sharma, 2020). • Organic materials are unequally distributed, with large amounts in livestock areas (i.e. north and southwest England) and lack of availability in eastern England.

Table 14: Strengths, weaknesses, opportunities and challenges (SWOT) in the regulatory framework for SSM measures related to grass and grazing management

Strengths	Weaknesses
• The FRfW (SI, 2018),and to some extent the SFI, encourage management practices that reduce the risk of soil damage and erosion from grassland (e.g. manage livestock to minimise compaction.) • Some voluntary schemes include grass and grazing management measures for avoiding soil damage and overgrazing.	• There is little formal regulation, with most SSM measures encouraged via guidance or voluntary schemes. • Some measures (e.g. reducing stocking rates, silvopasture) could lead to lower levels of production which may reduce farm incomes (although there is some evidence that lower input systems could be more resilient with similar or higher gross margins than higher input systems; Mihailescu *et al.,* 2014, 2015) and increase imports from countries where the environmental footprint of livestock production is greater than in England. • There is limited scientific evidence to show that changes in grazing management (e.g. from set stocked to rotational or mob) leads to improvements in soil quality in UK farming systems. A Defra funded study investigating the impact of 'mob-grazing' on soil quality and a range of ecosystem services is due to report in 2027.
Opportunities	**Threats**
• Home produced forage is the most economic animal feed. Improvements in grass production will reduce the need for bought in feed leading to lower farm and regional nutrient surpluses and associated environmental benefits. • The use of multi species swards rather than monoculture perennial ryegrass has the potential to improve the resilience of grass production to climate extremes (e.g. periods of drought), and benefit biodiversity. • Greater use of legumes in swards will reduce the need for manufactured nitrogen fertilisers to support crop growth, which will reduce the overall carbon footprint of grassland systems and increase their multifunctionality. • Managing stocking rates to reduce soil compaction may result in extended rest periods between grazing which may reduce the need for manufactured fertiliser inputs and improve plant species biodiversity. • Soils under permanent grassland are a significant carbon store that should be maintained to limit climate change. • Increased biodiversity and reduced stocking rates may increase the aesthetic value of grasslands, making them more attractive for recreational activities.	• Climate change with extended periods of drought may reduce the potential for grass production (e.g. changes to Grass Growth Class). • Changes in diet (i.e. reduction in consumption of red meat and dairy products) and the need to reduce GHG emissions may lead to a reduction in ruminant livestock production which will reduce the need for grass-based production systems (or reduce the intensity of those systems, resulting in greater multifunctionality; Schils *et al*., 2022). • Converting long-term grassland to arable land will increase the risk of soil degradation due to increased risk of erosion and loss of SOM and release carbon to the atmosphere.

Table 15: Strengths, weaknesses, opportunities and challenges (SWOT) in the regulatory framework for SSM measures related to <u>crops and rotations</u>.

<table>
<tr>
<td>Strengths
The FRfW (SI, 2018) encourage farmers to adapt practices that reduce the risks of soil erosion. For example: planting crops in early autumn and in dry conditions; planting headland rows and beds across the base of sloping land; undersowing or sowing a cover crop to stabilise soil after harvest; breaking up compacted soil; establishing grass buffer strips in valleys, along contours, slopes, field edges and gateways.
The SFI supports farmers to assess and improve soil quality including measuring SOM content (SAM1), establish soil cover over winter (SAM2) which will protect soils and reduce erosion risk, use herbal leys in arable systems (SAM3) which will enhance SOM.
There is an extensive scientific evidence base to underpin the benefits to soils of some of these measures (e.g. cover crops). Many UK farmers perceive cover crops as having a positive impact on their soil (Storr et al., 2019).
Some measures (e.g. cover cropping, diverse rotations), have a high rate of implementation (Dicks et al, 2018; Strauss et al, 2023).</td>
<td>Weaknesses
Some SSM measures (e.g. cover crop establishment) are dependent on soil type and weather. In general, cover crops should be established by late August to mid-September to have sufficient cover to reduce nitrate leaching losses and protect soils from damage. Additional cultivation operations to destroy cover crops maybe required to establish the following cash crop increasing the risk of soil compaction. In some cases the yield of the following crop can be reduced.
Ploughing out grassland may increase nitrate leaching losses in the season after destruction.
There is limited scientific evidence to support the benefits to soils from some measures (e.g. overwinter stubble)</td>
</tr>
<tr>
<td>Opportunities
Several SSM measures (e.g. cover crops, leys/rotational grass, intercropping, diverse rotations) have the potential to enhance biodiversity in arable systems.
Including grass (and livestock) or biomass crops in arable rotations has the potential to diversify farm businesses, increasing economic resilience.
Including grass in arable rotations has the potential to increase SOM, which can improve soil water infiltration, aggregate stability, nutrient turnover and crop available water supply on soils low in OM, which will improve crop production.
Diversifying rotations will provide a degree of resilience against future climate change scenarios.</td>
<td>Threats
Some SSM measures (e.g. cover cropping) are not always practical in high-risk situations such as following late harvested root crops.
Some SSM measures (e.g. establishing cover crops) adds costs to the business (seed and additional cultivations).
Establishing grass (and livestock) in arable systems is likely to require investment in farm infrastructure (e.g. water supply, fences etc.) as well as expertise in livestock husbandry.
Grass can act as a haven for soil nematodes. Consequently, introducing grass leys to arable rotations which include root crops and potatoes is likely to increase the length of the rotation to reduce the risk of crop damage by nematodes. Extending the rotation is likely to have economic and logistical implications for arable farmers.
Diversifying rotations on rented land may not be economically or practically possible due to the short-term nature of some tenancy agreements.</td>
</tr>
</table>

Table 16: Strengths, weaknesses, opportunities and challenges (SWOT) in the regulatory framework for SSM measures related to mechanical pressures

Strengths	Weaknesses
• The FRfW (SI, 2018) require soils to be manged to minimise the risk of soil erosion. Minimising the risk of soil compaction (e.g. by reducing trafficking especially when soils are wet) and alleviating the compaction when it occurs (e.g. cultivations at the depth of compaction) are important factors in reducing the risk of erosion. • Alleviating soil compaction can have many benefits including: maximising soil rooting which will ensure crops take up water and nutrients to optimise crop production minimising the risk of nitrate losses; maintaining and enhancing soil water infiltration, which will reduce flooding risk; providing optimum crop available water supply to support crop growth; and maintaining crop yields to sustain farm businesses. • There is an extensive scientific evidence base to underpin the benefits of some of these SSM measures (e.g. reduced tillage; reduced trafficking; reduced soil loads)	• Zero and reduced tillage are not suited to all soil or crop types. They are mostly suited to clay soils which can restructure following cycles of wetting and drying or freezing and thawing. Reduced and zero tillage techniques are most suitable for cereals, beans, oilseed rape and grass. • Cultivation practices are also controlled by weather conditions. If soils are wet, then it may not be possible to establish or harvest crops without causing soil compaction. The degree and depth of compaction will influence the appropriate cultivation interventions. • The number of factors that influence cultivation decisions make it difficult to have clear rules on how best to cultivate soils. Clear guidance and advice on how to minimise and alleviate soil compaction may be more appropriate. In some instances, if weather and soil conditions are particularly challenging at harvest then soil compaction will be inevitable, and it may take several years of interventions to restore the soil to good condition. • The scientific evidence base for some measures is limited (e.g. leave autumn seedbeds rough) or suggests that the measure may lead to further problems if not correctly implemented (e.g. subsoiling/soil loosening).
Opportunities	**Threats**
• Education and training for farmers would increase their understanding of soil management in particular identifying damaged soils that require interventions to improve soil structure. For example, the AHDB Soil Biology and Soil Health project produced simple easy to follow guidelines on soil management. In addition, and the SRUC Visual Evaluation of Soil Structure provides good information on how to assess the physical condition of soils. • Appropriate cultivation management will minimise labour, machinery and fuel costs.	• Climate change is likely to narrow the window for cultivations. Extreme periods of wet weather in the late summer/early autumn period will increase the risk of soil compaction as well as minimise the opportunity to alleviate any damage. • Supply chain demands often lead to high-risk root crops being harvested in inappropriate conditions (e.g. winter harvesting to ensure supplies over Christmas).

Table 17: Strengths, weaknesses, opportunities and challenges (SWOT) in the regulatory framework for SSM measures related to the physical environment

Strengths	**Weaknesses**
• Countryside Stewardship and SFI provide financial incentives to take high risk land out of production, introduce rest periods on productive land and extensify systems (e.g. pollen and nectar flower mix, legume fallow and silvopasture options). This will provide income to farmers whilst providing the opportunity to improve SOM and associated benefits. • The FRfW (SI, 2018) encourage the creation of physical barriers at field edges and on sloping land to control overland flow, which will reduce erosion and nutrient and sediment loss to water. Measures encouraged include: planting headland rows and beds across the base of sloping land; establishing grass buffer strips in valleys, along contours, slopes, field edges and gateways. • Installation of other landscape features such buffer strips and beetle banks can break the flow pathway from field to watercourse and these are encouraged by some Countryside Stewardship options. • There is extensive scientific evidence that maintaining and improving drainage schemes is important to reduce the risk of soil compaction by machinery and livestock, and maintain soils in good condition.	• Taking land out of production or changing to a less productive farming system is likely to require a change in farm practice, and may reduce farm income (although it may also increase economic and environmental resilience). • At a national scale, taking large areas of land out of production may increase the need for imports from countries where food production has a greater environmental footprint than in England. • Many of the interventions relating to changing land use, taking land out of production and installing new drainage can require long term planning to ensure impacts on farm businesses are minimised and that the changes in soil quality are effective. The short-term nature of many tenancy agreements may make implementing these interventions uneconomic or impractical. • Many measures would involve a significant one-time investment and ongoing maintenance costs (e.g. creating hard tracks for stock movement; introducing hedges), which may not be covered by existing grants.
Opportunities	**Threats**
• Changing land use from intensive arable production and introducing trees and hedges into the landscape has the potential to increase the aesthetic value of the countryside. Increases in plant and insect biodiversity may have positive benefits on bird populations and can create a more sustainable agricultural system. • Maintaining and replacing drainage systems can be expensive. However the costs can be recovered as a result of increased crop yields and reductions in cultivation and crop establishment costs. • Where buffer strips are installed it is likely that OM levels in the soil supporting the strips will increase in OM content and the above and belowground biodiversity should also increase. • Planting trees and hedges can also help stabilise soils and reduce runoff. Conversion of arable land into silvopasture or set aside will reduce erosion risk, increase SOM levels and enhance biodiversity.	• Extremes of weather conditions (drought/flooding) as a result of climate change are likely to impede the successful implementation of some of these practices. • Food security: without a reduction in food waste, taking large areas of land out of production would result in an increased reliance on imported food and the volatility of the global marketplace. • The practical enactment of these measures might be constrained by rental agreements.

Table 18: Strengths, weaknesses, opportunities and challenges (SWOT) in the regulatory framework for SSM measures related to <u>soil testing and monitoring</u>

Strengths	Weaknesses
• The Farming Rules for Water require soils to be tested very 5 years to inform planning of nutrient applications. • The SFI supports farmers to assess soil quality including measuring SOM content (SAM1) and producing a soil management plan. • There is a large volume of educational materials supporting the provision of SSM measures. • Free educational events and initiatives are provided by bodies such as AHDB and CSF, and can include advice on and demonstration of, SSM. This is complemented with paid-for courses provided by e.g. BASIS and BSSS. • A Soil Scientist Level 7 Apprenticeship has recently been approved (October 2023).	• Although there is a large level of educational material and various initiatives supporting education, training, and advice, it is fragmented and inconsistent (Ingram & Mills, 2018), with concern expressed about "knowledge gaps" for farmers in relation to SSM (Hou *et al.*, 2020). • Education and training can be costly, as can regular soil testing. • The capacity of laboratories for testing, and provision/training of soil scientists, is limited. This has repercussions on the time needed for testing and availability of advice.
Opportunities	**Threats**
• There is the potential to improve and expand on the provision of training and advice on SSM so that is it less 'ad hoc' and fragmented. This is likely to lead to a greater uptake of practices with improvements in soil quality, biodiversity and a reduction in emissions to the environment. • A survey of UK arable farms implementing SSM listed training for staff within the ten highest priorities (Dicks *et al*,. 2018) • National soil monitoring metrics and priorities can be very different to those at a farm level. Greater on-farm monitoring (by farmers) at a field level will enable them to target interventions more effectively, leading to improvements in soil quality, crop performance and lower input costs. • National soil monitoring schemes provide valuable data on the state and condition of soils over time. These should be continued, particularly given predicted changes in climate and land use. Current schemes include the UKCEH Countryside Survey and the England Ecosystem Survey (EES). • Making soils data publicly available and free to access would assist farmers to monitor and improve the health of their soils.	• The number of soil scientists has reduced over recent years, with those who have retired not being replaced. There are also only a limited number of institutes providing soil science training. • The quality and accuracy of advice and learning cannot be guaranteed unless it is delivered by suitably qualified and accredited trainers. This is particularly pertinent in relation to facilitated peer-to-peer learning (whilst acknowledging that this can be a very effective KE mechanism). Some literature sources expressed concerns that those advising farmers on SSM might also have "knowledge gaps" (Hou *et al*, 2020). • There is considerable debate on what soil metrics are most appropriate for both on-farm and national scale monitoring, and how they should be interpreted. Given the diversity of soils, land-uses and agroclimatic conditions in England it is hard (and potentially impossible for some indicators) to define thresholds or benchmarks. Using inappropriate or inaccurate metrics and benchmarks could undermine confidence in soil monitoring or lead to incorrect (and potentially damaging) soil management interventions.

9 SUMMARY AND CONCLUSIONS

Improving soil management is a key action under Goal 6 (Using Resources from Nature Sustainably) of the revised Environmental Improvement Plan for England. Defra has committed to support farmers to bring 40% of agricultural soils in England under sustainable management by 2028 and increase this to 60% by 2030 (Defra, 2023). In the light of this commitment, this project aimed to critically appraise the current regulatory and governance frameworks, and government and non-government schemes supporting the sustainable management of agricultural soils in England, to assess the strengths and weaknesses of the existing legislative framework and voluntary schemes.

Sustainable soil management - definition

An initial review of the recently published literature review (post-2015) found that whilst many authors and international organisations (including the UN FAO) have attempted to define the term 'sustainable soil management' there was no universally accepted definition and no broadly accepted definition for England (see Section 3.1). Given this lack of a clear definition, together with a lack of consensus over the metrics to be used for measuring changes in soil quality and the challenges associated with national scale soil testing and monitoring, it is difficult to understand how an objective to increase the percentage of agricultural soils managed sustainably could be monitored.

Sustainable soil management – the evidence base on practices & climate impacts

The literature sources identified considerable numbers of soil and land management measures that could contribute to SSM. These were grouped according into five broad categories of measures (c. 50 individual measures) that are or could be applied in the context of English agricultural soils, with a sixth category related to soil testing and monitoring, education and advice. The scientific evidence base relating to the benefits of each measure in terms of improving soil quality was briefly summarised, together with any associated risks or issues (see Section 5). Scientific research on topics related to some of the measures was comprehensive. There is, for example a very large body of evidence collated over many years (from the UK and elsewhere in the world) on how applications of organic materials of various types can increase SOM, leading to improvements in other indicators of soil health such as nutrient supply, soil structure, bulk density, water holding capacity, microbial biomass and earthworm numbers, and reduced erosion and compaction risks. Similarly, there is a very large body of work that has investigated the impact of no- and reduced-tillage practices on various soil properties and many reviews of the topic. However, there is inconsistency in the literature regarding the impacts of adopting reduced tillage practices on soil quality due to the variation in the practices used and the impacts of different cropping systems, soil types and climate. Other potential SSM measures have been less well researched or lack evidence in an English context (e.g. measures relating to grass and grazing management), whilst some are still at the speculative stage or have not been proven to be effective for soils in England (see Section 5.7).

Climate change will have important implications for SSM and the measures that can and should be adopted. Under future climate change scenarios, soil inputs and other SSM measures that build or maintain SOM levels will become increasingly important. Organic matter improves soil fertility, structure and stability, providing protection against an increased level of threat. However, extremes of weather conditions (drought and flooding) as a result of climate change are likely to impede the successful implementation of some SSM measures particularly those related to the physical environment.

Sustainable soil management – legislation and voluntary schemes

The mapping of SSM measures to existing regulations and voluntary schemes revealed that the majority of the existing legislation that could be directly linked to SSM focused on controlling soil inputs to agricultural soils via non-farm organic materials such as biosolids, compost and digestates or manufactured fertiliser. Regulations such as the Sludge (Use in Agriculture) Regulations 1989 (SI, 1989) and the Fertiliser Regulations (EC, 2019), have a specific goal of reducing the risk of soil contamination (e.g. from pathogens, PTEs or organic chemical contaminants) following application of these materials to land. There is little focus on other aspects of soil protection such as reducing the threat of soil loss, compaction or erosion. Regulatory controls in the FRfW (SI, 2018) and the Nitrate Pollution Prevention Regulations 2015 (SI, 2015; 2016) make reference to many of the SSM measures identified in the literature, however they are not primarily targeted at promoting SSM *per se* and no specific guidance is provided on how to manage soils sustainably. Instead, they focus on the protection of watercourses from nutrient and sediment pollution, with any benefits to soils (e.g. by limiting compaction and erosion) seen as secondary to water quality improvements.

Whilst legislation may be lacking for the reasons described above, voluntary government-funded schemes such as the SFI and Countryside Stewardship provide incentives for farmers to adopt sustainable farming practices, with some SFI actions supporting farmers to assess and improve soil quality. The driving force behind many of the measures within these schemes is on improving biodiversity and providing wider environmental benefits, with any benefits to soils appearing to be more of a secondary benefit or 'side-effect'.

Some SSM measures were not covered by legislation or government schemes but have been addressed by private voluntary schemes aiming to encourage farmers to adopt practices that support their particular ethos. For example, some schemes promoting regenerative agriculture encourage participating farmers to adopt conservation tillage practices to control erosion, preserve moisture, and promote soil health. Such practices cannot be required by law as they are not appropriate for all soil types and weather conditions, may require considerable infrastructure changes by participants and in some cases are not well defined.

Sustainable soil management – case studies

Three best practice case studies were selected to demonstrate how regulatory and governance frameworks can support SSM in England. The selected farms covered a range of geographical areas, cropping systems and soil types. All three case studies recognized the need (and strongly desired) to maintain and improve soil quality/health and minimise environmental impacts, and had adopted many of the SSM practices outlined in this review in order to try to achieve this. However, the over-riding and primary driver for all decisions on farm was financial, with SFI and CS payments seen as essential (although potentially inadequate) to support SSM. *"There is no excuse for not doing the right thing if you are making money, however if you're not then it's difficult to think environmentally"*

Outcome of SWOT analysis and conclusions

This review and SWOT analysis has demonstrated that it is difficult to legislate for SSM (or indeed for soil protection in general). One reason for this is that there is no consensus on the definition of a 'healthy' or 'good quality' soil, how to measure whether a soil is 'healthy' or what measures might be required to ensure a soil is managed sustainably. Appropriate management practices will vary depending on the function that the soil is required to fulfill e.g. to provide food or to grow energy crops, to act as a buffer against flooding, to provide a habitat for biodiversity, or (most likely) to provide a combination of functions. Even when focusing on a single function, such as food production, defining appropriate SSM measures is not straightforward as it will depend on the farming system, soil type, drainage, topography, weather conditions and other factors outside a land manager's immediate control (e.g. supply chain demands). For example, no or reduced tillage is more suited to clay soils, whereas cover cropping can sometimes be difficult on these soil types. Moreover, what might be appropriate one season, may not be possible in the following season e.g. due to differences in weather or crop type. Consequently, there is 'no one size fits all' approach when it comes to the SSM measures that may need to be implemented to support a soil to provide these various functions.

Legislating for SSM is also likely to be difficult to implement (except in relation to preventing contamination or pollution of watercourses, e.g. Water Resources Act 1991). It should be noted that feedback from the EU on the effectiveness of CAP measures and actions relevant to manure management in the Nitrates Directive (EC, 1991) has not been encouraging (see Section 6.3). It is extremely difficult to police legislation where there is no clear definition of what is required and where SSM measures are so dependent on local conditions. This has been an issue with implementation of the FRfW where farmers are required to take 'reasonable precautions to prevent agricultural diffuse pollution resulting from (nutrient) applications' and to 'not exceed the (nutrient) needs of the crop and soil on that land'. Lack of clarity over what this wording means in practice and how it should be regulated has led to confusion within the industry (e.g. https://www.nfuonline.com/updates-and-information/farming-rules-for-water-river-action-court-case/).

Other issues associated with legislating for SSM identified in the SWOT analysis include the potential risk that measures introduced to address one soil issue may inadvertently result in damaging the soil in a different way. There may be a requirement for additional or specialised machinery and equipment, or for more specialised staff. Thus, the cost of compliance can be high. Implementing regulations at the national scale can be difficult due to the lack of trained regulators and the need for farmers to provide comprehensive records to demonstrate compliance.

The SWOT analysis also identified several SSM measures that would be difficult to implement on tenanted land for economic or practical reasons related to the short-term nature of some tenancy agreements. A relatively straightforward approach to encouraging SSM might be to require tenancy agreements to contain clauses relating to adopting SSM practices throughout the agreement period and leaving soils in good condition at the end of the rental period (although the latter would require clear specification of the soil quality metrics and measurement methods to be used).

In the light of these findings, the adoption of many SSM practices is likely to be more effectively encouraged by voluntary schemes rather than legislated for at a national level, with farmers able to 'select' those practices that are most appropriate to their locality and farming system. Consequently, it may be prudent to shift the focus onto voluntary 'compliance' through financial incentives (e.g. income foregone and payment for ecosystem services), and encourage this via improved education, 'green nudges' (Schubert, 2017) and knowledge exchange. Indeed, there is potential to improve and expand on the provision of training and advice on SSM so that it is less 'adhoc' and fragmented. As suggested by Ingram & Mills (2018), there is a need to increase awareness of the value of soil and its many functions, with the focus moving away from improving single soil functions or addressing a specific soil threat, or meeting individual regulatory, grant or voluntary scheme requirements, towards a recognition of the importance of soil ecosystem services (the public and private goods provided by healthy soils) and a more holistic approach to SSM.

10 REFERENCES

Abhiram, G. & Eeswaran, R. (2022). Legumes for efficient utilization of summer fallow. In: *Advances in Legumes for Sustainable Intensification*. pp 51-70

ADAS (2007). *Diffuse nitrate pollution from agriculture – strategies for reducing nitrate leaching*. ADAS report to Defra – supporting paper D3 for the consultation on implementation of the Nitrates Directive in England, July 2007.

AHDB (2019). *Nutrient Management Guide (RB209*). https://ahdb.org.uk/nutrient-management-guide-rb209

AHDB (2023). *Healthy grassland soils*. https://projectblue.blob.core.windows.net/media/Default/Imported%20Publication%20Docs/HealthyGrasslandSoils_230712_WEB.pdf

Alliance Environment (2020). *Evaluation support study on the impact of the CAP on Sustainable Management of the Soil, European Commission*. https://www.ecologic.eu/sites/default/files/publication/2022/3591-Evaluation-Support-Study-on-The-Impact-of-The-CAP-on-Sustainable-Management-of-The-Soil-web.pdf

Altobelli, F. *et al* (2020). Improving soil and water conservation and ecosystem services by sustainable soil management practices: From a global to an Italian soil partnership. *Ital. J. Agron.,* 15, 1765.

Amelung, W. *et al*. (2020). Towards a global-scale soil climate mitigation strategy. *Nat. Commun*. 11, 5427.

Anejionu, O. & Woods, J. (2019). Preliminary farm-level estimation of 20-year impact of introduction of energy crops in conventional farms in the UK. *Renew. Sustain. Energy Rev.,* 116, 109407

Antille, D. *et al* (2019). Review: Soil compaction and controlled traffic farming in arable and grass cropping systems. *Agron. Res*. 17, 653–682

Baker, J (2024). Environmental land management in 2024: details of actions and payments. Defra. https://defrafarming.blog.gov.uk/2024/01/04/environmental-land-management-in-2024-details-of-actions-and-payments/

Ball, B.C. *et al.* (2005) The role of crop rotations in determining soil structure and crop growth conditions. *Canadian J. Soil Sci*., 85, 557-577

Balshaw, H. *et al*. (2014). *Identifying the soil protection benefits and impact on productivity provided by the access to waterlogged land requirements in cross compliance and exploring the impacts of prolonged waterlogging on soil quality and productivity*. Defra Project SP1316, Subprojects A & B. http://sciencesearch.defra.gov.uk

Bateman, A. *et al*. (2011). Closing the phosphorus loop in England: the spatio-temporal balance of phosphorus capture from manure versus crop demand for fertiliser. *Resour. Conserv. Recycl*. 55, 1146–1153.

Batey, T. (2009. Soil compaction and soil management - a review. *Soil Use Manage*, 25, 335-345.

Beaumelle, L. *et al* (2023). Pesticide effects on soil fauna communities—A meta-analysis. *J. Appl. Ecol.*, 60, 1239-1253

Beillouin, D. *et al.* (2023). A global meta-analysis of soil organic carbon in the Anthropocene. *Nat. Comm*., 14, 3700.

Bell, M. *et al* (2016) How do emission rates and emission factors for nitrous oxide and ammonia vary with manure type and time of application in a Scottish farmland? *Geoderma*, 264, 81-93.

Beltran, I. *et al*. (2020) DATAMAN: A global database of nitrous oxide and ammonia emission factors for excreta deposited by livestock and land-applied manure. *J. Environ. Qual*., 50, 513-527

Berdeni, D. *et al*. (2021). Rectifying Soil Structural Damage. AHDB Project report No. 91140002-14. 69 pp.

Bhogal, A. *et al*. (2007). *Effects of reduced tillage practices and organic material additions on the carbon content of arable soils*. Final report to Defra for project SP0561.

Bhogal A. *et al*. (2009). Best Practice for Managing Soil Organic Matter in Agriculture. Manual of Methods for 'Lowland' Agriculture. Prepared as part of Defra project SP08016. https://randd.defra.gov.uk/ProjectDetails?ProjectId=15536

Bhogal, A. *et al*. (2018). Improvements in the quality of agricultural soils following organic material additions depend on both the quantity and quality of the materials applied. *Front. Sustain. Food* Syst. 2, 9.

Bhogal, A. *et a*l. (2018). Structural condition of agricultural soils in the UK. *International Fertiliser Society Proceedings* 829

Bhogal, A. *et al*. (2020). *Maxi Cover Crop: Maximising the benefits from cover crops through species selection and crop management*. Final report for AHDB Project No. 620.

Bhogal, A. *et al* (2022). Novel Fertilisers: A rapid evidence synthesis. Final reports for Defra project NM0103. https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=20595

Blanco-Canqui, H. & Ruis, S. (2018). No-tillage and soil physical environment. *Geoderma*, 326, 164-200

Błaszkiewicz, Z. (2019). Identification and quantification of selected factors determining soil compression by tractors of weights with single wheels and dual wheels, *J. Res. Applications. Agric. Eng.* 64, 4-12.

Boardman, J. & Favis-Mortlock, D. (2023). The significance of drilling date and crop cover with reference to soil erosion by water, with implications for mitigating erosion on agricultural land in South East England. *Soil Use Manage*., 39,40-47.

Boardman, J. & Vandaele, K. (2023). Soil erosion and runoff: The need to rethink mitigation strategies for sustainable agricultural landscapes in western Europe. *Soil Use Manage*., 39, 673-685.

BSSS (2021). *Science Note: Soil Carbon*. British Society of Soil Science. https://soils.org.uk/wp-content/uploads/2022/05/BSSS_Science-Note_Soil-Carbon_Final_May22_75YRS_DIGITAL.pdf

Burak, E. & Sakrabani, R. (2023). Novel carbon capture-based organo-mineral fertilisers show comparable yields and impacts on soil health to mineral fertiliser across two cereal crop field trials in Eastern. *Field Crops Res.*, 302, 109043

Burgess. P.J. *et al.* (2023). *Evaluating agroecological farming practices*. Report from the "Evaluating the productivity, environmental sustainability and wider impacts of agroecological compared to conventional farming systems" project SCF0321 for DEFRA. Cranfield University and UK Centre for Ecology and Hydrology.

Case, S.D.C. *et al.* (2017). Farmer perceptions and use of organic waste products as fertilisers – A survey study of potential benefits and barriers. *Agric. Syst.*, 151, 84-95.

Chambers, B. J. *et al*. (2013) Biosolids Nutrient Management Matrix. 18th European Biosolids & Organic Resources Conference. Manchester, November 2013

Chamen, T.W.C. *et al*. (2015). Mitigating arable soil compaction: A review and analysis of available cost and benefit data. *Soil Tillage Res*. 146, 10–25.

Chaplot, V. & Smith, P. (2023). Cover crops do not increase soil organic carbon stocks as much as has been claimed: What is the way forward? *Glob. Chang. Biol.*, 29(22), 6163–6169.

Chapman, P.J. *et al.* (2018). *Agricultural Land Management for Public Goods Delivery: iCASP Evidence Review on Soil Health*. Yorkshire Integrated Catchment Solutions Programme (iCASP) Report.

Charlton, A. *et al*. (2016a). Long-term impact of sewage sludge application on soil microbial biomass: An evaluation using meta-analysis. *Environmental Pollution*, 219, 1021-1035.

Charlton, A. *et al*. (2016b). Long-term impact of sewage sludge application on Rhizobium Leguminisorum Biovar Trifolii – an Evaluation using Meta-Analysis. *Journal of Environmental Quality*. 45, 1572-1587.

Chen, H. *et al.* (2023). Straw amendment and nitrification inhibitor controlling N losses and immobilization in a soil cooling-warming experiment. *Sci. Total Environ*., 870, 162007

Chivers, C-A (2021). *Exploring the efficacy of Catchment Sensitive Farming advice and examining ways of improving its delivery through the lens of credibility, relevance and legitimacy*. PhD Thesis, University of Exeter.

Cole, L. J. *et al.* (2020) Managing riparian buffer strips to optimise ecosystem services: A review. *Agric. Ecosyst. Environ*., 296, 106891.

Collier, S. M. *et al.* (2020). Effect of farm management on topsoil organic carbon and aggregate stability in water: A case study from Southwest England, UK. *Soil Use Manage*. 37: 49-62.

Collins, A.L. *et al.* (2018). Assessing the potential impacts of a revised set of on-farm nutrient and sediment 'basic' control measures for reducing agricultural diffuse pollution across England. Sci. Total Environ., 621, 1499-1511.

Conant, R. T. *et al.* (2017) Grassland management impacts on soil carbon stocks: a new synthesis. *Ecol. Appl*., 27, 662–668

Cong, P. *et al.* (2016). Effects of stubble and mulching on soil erosion by wind in semi-arid China. *Sci. Rep.* 6, 29966

Cooper, R. J. *et al* (2020) Conservation tillage and soil health: Lessons from a 5-year UK farm trial (2013–2018). *Soil Tillage Res*., 202, 104648

Cooledge, E.C. *et al*. (2022) Agronomic and environmental benefits of reintroducing herb- and legume-rich multispecies leys into arable rotations – a review. Frontiers in Agricultural Science and Engineering, 9, 245-271.

De Vries, F. T. *et al*. (2021). Extensive Management Promotes Plant and Microbial Nitrogen Retention in Temperate Grassland. *PLOS ONE*. 7, e51201

Defra (2009). *Protecting our Water, Soil and Air. A Code of Good Agricultural Practice for farmers, growers and land managers*. TSO.

Defra (2023). *Environmental Improvement Plan 2023*. www.gov.uk/government/publications/environmental-improvement-plan

Defra (2024). Spotlight on new actions: agroforestry and improvements to our trees and woodland offer. Defra. Accessed February 2024 at Spotlight on new actions: agroforestry and improvements to our trees and woodland offer – Farming (blog.gov.uk)

Deleebeeck N. *et al*. (2021). *Contaminants in fertilisers: Assessment of the risks from their presence and socio-economic impacts of a possible restriction under REACH*, Report to the European Commission, by ARCADIS.

Dick, W. A. (2018). *Crop and Environmental Benefits of Gypsum As a Soil Amendment*. 2018 ASA and CSSA Meeting, Baltimore, USA

Dicks, L. V. *et al.* (2018). What agricultural practices are most likely to deliver "sustainable intensification" in the UK? *Food Energy Secur.*, 8, e00148.

Dicks, L.V. *et al*. (2020) Farmland Conservation. in: W.J. Sutherland *et al.* (eds) *What Works in Conservation 2020*. Open Book Publishers, Cambridge, UK. pp 283-321

DoE (1996). *Code of Practice For Agriculture Use Of Sewage Sludge*. Department of the Environment.

Donnison, C. *et al.* (2021). Land-use change from food to energy: meta-analysis unravels effects of bioenergy on biodiversity and cultural ecosystem services. *Environ. Res. Lett*. 16 113005

Dowers, J. *et al.* (2023). *Understanding Rotational "Mob" Grazing: Impacts, Benefits and Trade-offs, Rapid Evidence Assessment.* Final Reports for Defra project SCF0226.

EA (2015). *Recycled gypsum from waste plasterboard: quality protocol.* https://www.gov.uk/government/publications/recycled-gypsum-from-waste-plasterboard-quality-protocol.

EA (2019). The state of the environment: soil. Environment Agency. https://www.gov.uk/government/publications/state-of-the-environment/summary-state-of-the-environment-soil

EC (1991). *Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC).* https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01991L0676-20081211

EC (2019). *Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending*

Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1009

EC (2021). *Questions and Answers on the EU Soil Strategy.* https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_5917

EC (2023). *Soil Health*. Soil health - European Commission (europa.eu)

Edwards, C.A. & Arancon, N.Q. (2022). The Influence of Environmental Factors on Earthworms. In: *Biology and Ecology of Earthworms*. Springer, New York, NY. https://doi.org/10.1007/978-0-387-74943-3_7

Elias, D. M. O. *et al*. (2023). The potential to increase grassland soil C stocks by extending reseeding intervals is dependent on soil texture and depth. J. Environ. Manage., 334, 117465

European Court of Auditors (2023). *Special report: EU Efforts for Sustainable Soil Management. Unambitious standards and limited targeting*. European Court of Auditors. https://www.eca.europa.eu/ECAPublications/SR-2023-19/SR-2023-19_EN.pdf.

Evans, R. (2017). Factors controlling soil erosion and runoff and their impacts in the upper Wissey catchment, Norfolk, England: A ten-year monitoring programme: Monitoring Soil Erosion and its impacts, Norfolk, England. *Earth Surf. Process. Landf.,* 42, 2266-2279

Eze, S. *et al.* (2018). Soil organic carbon stock in grasslands: Effects of inorganic fertilizers, liming and grazing in different climate settings. *J. Environ. Manag*., 223, 74-84

Faber, M & Montforts, M. H. M. M. (2022). *Organic contaminants in fertilising products and components materials*. WOt-technical report 220 (wur.nl)

FAO (2017). *Voluntary Guidelines for Sustainable Soil Management*. Food and Agriculture Organization of the United Nations, Rome.

FAO/ITPS (2020). *Towards a definition of soil health*, ITPS Soil Letters #1. https://www.fao.org/documents/card/en?details=cb1110en/

Feigenwinter I., 2022: Greenhouse gas fluxes (CO2, N2O, CH4) from temperate grassland on different spatio-temporal scales: budgets, drivers, processes. Doctoral thesis, ETH Zurich. https://doi.org/10.3929/ethz-b-000580877.

Fornara, D. & Higgins, A. (2022). Tillage and reseeding effects on soil carbon stocks: evidence from 500 agricultural grasslands in the UK. *Agron. Sustain. Dev*., 42, 71.

Fu, B. *et al*. (2021). Impacts of crop residues on soil health: a review. *Env. Pollut. Bioavail*. 33, 164-173

Ghosh, U. & Daigh, A. L. M. (2020). Soil compaction problems and subsoiling effects on potato crops; A review. *Crop Forage Turfgrass Manag.*, 6, e20030

Gibbs, P.A. *et al*. (2006a). Initial results from long-term field studies at three sites on the effects of heavy metal-amended liquid sludges on soil microbial activity. *Soil Use Manag.* 22, 180-187

Gibbs, P.A. *et al*. (2006b). Initial results from a long-term, multi-site field study of the effects on soil fertility and microbial activity of sludge cakes containing heavy metals. *Soil Use Manag.* 22, 11-21.

Giller, K.E. *et al.* (2021) Regenerative agriculture: an agronomic perspective. *Outlook Agric.* 50, 13-25

Godwin, R.J. & Spoor, G. (2015). Choosing and evaluating soil improvements by subsoiling and compaction control. In Ball, B. C. & Munkholm, L. J. (eds). *Visual Soil Evaluation: Realising Potential Crop Production with Minimum Environmental Impact*. CABI, Wallingford, UK.

Gosling, P. *et al*. (2017). Converting highly productive arable cropland in Europe to grassland: –a poor candidate for carbon sequestration. *Sci. Rep.*, 7, 10493

Goulding, K. W. T. (2016). Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. *Soil Use Manag*., 32, 390-399.

Gregory, A. S. *et al.* (2015). A review of the impacts of degradation threats on soil properties in the UK. *Soil Use Manage*, 31,1-15.

Hamza, M. A. & Anderson, W. K. (2011). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil Tillage Res*., 82, 121-145

Harper Adams (2021) News - Harper Adams University research suggests running low pressure tyres can boost farmers' yields | Harper Adams University (harper-adams.ac.uk)

Harris, M., *et al.* (2023). *Towards Indicators of Soil Health*. JNCC Report 737. https://data.jncc.gov.uk/data/71cece04-eef3-4d34-b118-33ddad50912c/jncc-report-737.pdf

HC (2023). House of Commons. Environment, Food and Rural Affairs Committee. *Soil health. First Report of Session 2023–24*. https://publications.parliament.uk/pa/cm5804/cmselect/cmenvfru/245/report.html

Hejnowicz, A.P. *et al*. (2016). A survey exploring private farm advisor perspectives of agri-environment schemes: The case of England's Environmental Stewardship programme. *Land Use Policy*, 55, 240-256.

Hill, K. *et al*. (2015) *Field drainage guide*. https://agricology.co.uk/resource/field-drainage-guide/

Holden, J. *et al.* (2019) The role of hedgerows in soil functioning within agricultural landscapes. *Agric. Ecosyst. Environ*., 273, 1-12.

Holland, J. E. *et al*. (2018). Liming impacts on soils, crops and biodiversity in the UK: A review. *Sci. Total Environ*., 610–611, 316-332

Hou, D. (2020). Knowledge sharing and adoption behaviour: An imperative to promote sustainable soil use and management. *Soil Use Manage*., 36, 557-560

Hou, D. (2021). Sustainable soil management and climate change mitigation. *Soil Use. Manage*., 37, 220-223

Hou, D. *et al.* (2020). Sustainable soil use and management: An interdisciplinary and systematic approach. *Sci. Total Environ*. 729, 138961

Hu *et al*. (2019). Converting temperate long-term arable land into semi-natural grassland: decadal-scale changes in topsoil C, N, 13C and 15N contents. *Eur. J. Soil Sci*., 70, 350-360

Humphries, R N & Brazier, R E (2018). Exploring the case for a national-scale soil conservation and soil condition framework for evaluating and reporting on environmental and land use policies. *Soil Use Manage*., 34 (1), 134-146.

Hurley, P.D. *et al.* (2023). *Barriers and Enablers to Uptake of Agroecological and Regenerative Practices, and Stakeholder Views towards 'Living Labs'*. Report from the "Evaluating the productivity, environmental sustainability and wider impacts of agroecological compared to conventional farming systems" project SCF0321 for DEFRA. Cranfield University and UK Centre for Ecology and Hydrology

Ingram, J. & Mills, J. (2018). Are advisory services "fit for purpose" to support sustainable soil management? An assessment of advice in Europe. *Soil Use Manag*., 35, 21-31.

Jaafar, M. & Waling, D. E. (2010). Assessing the Impact of Fodder Maize Cultivation on Soil Erosion in the UK. In: *Land Degradation and Desertification: Assessment, Mitigation and Remediation*

Jarvis, N. *et al*. (2017). Long-term effects of grass-clover leys on the structure of a silt loam soil in a cold climate. *Agric. Ecosyst. Environ*. 247, 319–328

Jaworski, C. C. *et al*. (2024). Sustainable soil management in the United Kingdom: A survey of current practices and how they relate to the principles of regenerative agriculture. *Soil Use Manage*. E12908.

Jayaraman, S. *et al.* (2023). Soil Sustainable Management: Challenges, Prospects and Benefits. In: *Sustainable Soil Management: Beyond Food Production*. Cambridge Scholars Publishing.

Johnsen, K. *et al.* (2001). Pesticide effects on bacterial diversity in agricultural soils – a review. *Biol Fertil Soils* 33, 443–453

Johnston, A. E. *et al.* (2009). Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *Adv. Agron*. 101, 1–57.

Johnston, A. E. *et al*. (2017). Changes in soil organic matter over 70 years in continuous arable and ley–arable rotations on a sandy loam soil in England. *Eur. J. Soil Sci.*, 68, 305–316

Jones, N. *et al*. (2019). *The Environmental Effectiveness of the Countryside Stewardship scheme; Establishing a baseline agreement monitoring sample*. Final Report. REF: ECM47452/22965

Keestra, S. D. *et al*. (2023). European agricultural soil management: towards climate-smart and sustainability, knowledge needs and research approaches. *Eur. J Soil Sci*., 75, e13437

Kell, D. B. (2011). Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water sequestration, *Ann. Bot.*, 108 407–418,

Kleinman, P.J.A.. *et al*. (2015). Implementing agricultural phosphorus science and management to combat eutrophication. *AMBIO* 44 (Suppl 2), 297–310

Knox, J.W. *et al.* (2020). Irrigation water strategy for UK agriculture and horticulture. https://www.ukia.org/3d-flip-book/irrigation-strategy-2020a/

Koninger, J. *et al. (*2021) Manure management and soil biodiversity: Towards more sustainable food systems in the EU. *Agric. Syst*, 194, 103251

Kort, J. *et al* (1998). A review of soil erosion potential associated with biomass crops. *Biomass Bioenergy*, 14, 351-359.

Lilly, A. *et al.* (2018). *Soil erosion and compaction in Scottish soils: adapting to a changing climate*. soil-erosion-and-compaction-in-scottish-soils-adapting-to-a-changing-climate.pdf (climatexchange.org.uk)

Liu, H. *et al*. (2018) Effects of standing stubble on the interception of soil erosion particles. *Land Degrad Develop*., 30, 328-336.

Lowth, H. (2023). *Living Mulches. Final report 2020-2022*. https://agricology.co.uk/wp-content/uploads/2023/01/IF-LM-Final-report_2022.pdf

MAFF/DOE (1993). *Review of the Rules for Sludge Application to Agricultural Land: Soil Fertility Aspects of Potentially Toxic Elements*. Report of the Independent Scientific Committee. MAFF/DoE, November 1993, 91pp.

Magistrali, A. *et al.* (2022). *Identifying and implementing regenerative agriculture practices in challenging environments: experiences of farmers in the north of England*. AHDB Project Report No. PR640-09

Marchuk, S. *et al*. (2023). Biosolids-derived fertilisers: A review of challenges and opportunities. *Sci Total Environ*., 875, 162555

Marini, M. *et al.* (2020). The new fertilizer regulation: A starting point for cadmium control in European arable soils? *Sci. Total Environ*., 745, 140876.

Marriott, C. A. *et al*. (2010) Impacts of extensive grazing and abandonment on grassland soils and productivity, *Agric. Ecosyst. Environ.*, 139, 476-482,

Martin, G. *et al* (2020) Role of ley pastures in tomorrow's cropping systems. A review. *Agron. Sustain Dev*., 40, 17

McBratney, A. *et a*l. (2014). The dimensions of soil security. *Geoderma*, 213, 2013-213

McGuire, R. *et al.* (2022). Potential Co-benefits and trade-offs between improved soil management, climate change mitigation and agri-food productivity. *Food Energy Security*, 11, e352.

McTavish, M. J. *et al*. (2021). Sustainable management of grassland soils. In: *Soils and Landscape Restor*ation. pp.95-124.

Mehra, P. *et al*. (2018) Chapter Five - A Review of Tillage Practices and Their Potential to Impact the Soil Carbon Dynamics. *Adv Agron*., 150, 185-230

Mihailescu, E. *et al*. (2014). Nitrogen balance and use efficiency on twenty-one intensive grass-based dairy farms in the South of Ireland. *Journal of Agricultural Science*, 152, 843-859.

Mihailescu, E. *et al*. (2015). Economic impacts of nitrogen and phosphorus use efficiency on nineteen intensive grass-based dairy farms in the South of Ireland. *Agricultural Systems*, 132, 121-132.

Montgomery, I. *et al*. (2020). Hedgerows as Ecosystems: Service Delivery, Management, and Restoration. *Annu. Rev. Ecol. Evol. Sy*st. 51, 81–102

Mouazen, A.M. & Palmqvist, M. (2015). Development of a Framework for the Evaluation of the Environmental Benefits of Controlled Traffic Farming. *Sustainability* 7, 8684-8708.

Mullholland, B. *et al.* (2029). *Literature Review: Defra Project SP1218. An assessment of the potential for paludiculture in England and Wales*. https://lowlandpeat.ceh.ac.uk/sites/default/files/2022-07/Defra-LP2-paludiculture-report-April-2020.pdf

NE (2022). *Paludiculture – the future of farming on peat soils?* https://naturalengland.blog.gov.uk/2022/09/30/paludiculture-the-future-of-farming-on-peat-soils/

Nemecek, T. *et al*. (2008) Environmental impacts of introducing grain legumes into European crop rotations. *Eur. J. Agron*., 28, 380-393

New Scientist (2024) https://www.newscientist.com/article/2413702-huge-amounts-of-rock-dust-are-being-spread-across-farms-to-capture-co2/

Newell-Price, J.P. *et al*. (2014). Managing grasslands to mitigate flooding risk. In: '*EGF at 50: The Future of European Grasslands*. Proceedings of the 25th General Meeting of the European Grassland Federation, Aberystwyth, Wales, September 2014. .

Nicholson, F. A. *et al.* (2014). *Straw incorporation review*. HGCA Research Review No. 81. https://projectblue.blob.core.windows.net/media/Default/Research%20Papers/Cereals%20and%20Oilseed/rr81-web.pdf

Nicholson, F. A. *et al.* (2017). Nitrogen losses to the environment following food-based digestate and compost applications to agricultural land in England and Wales. *Environ. Pollut*., 228, 504-516

Nicholson, F. A. *et al*. (2022). Assessing the effect of biosolids on soil health. In: *Improving Soil Health* (Ed. W. Horwarth). Burleigh Dodds, Cambridge.

Nicholson, F. A. *et al*. (2024). *Improved Forage Systems: Update of the ForaGIN report*. Report for Defra project 30120

Nielson, D. C. & Calderon, F. J. (2011). *Fallow effects on soil*. Publications from USDA-ARS / UNL Faculty. 1391. https://digitalcommons.unl.edu/usdaarsfacpub/1391

Norton, L. *et al*. (2022). Learning from innovative practitioners: Evidence for the sustainability and resilience of pasture fed livestock systems. *Front. Sustain. Food Syst*., 6. https://doi.org/10.3389/fsufs.2022.1012691

O'Callaghan, M. *et al.* (2022). Soil microbial inoculants for sustainable agriculture: Limitations and opportunities. *Soil Use. Manag*., 38, 1340-1369.

Ockenden, M. C. *et al*. (2017). Major agricultural changes required to mitigate phosphorus losses under climate change. *Nat Commun.,* 8, 161.

Palmer, R. C. & Smith, R. P. (2013). Soil structural degradation in SW England and its impact on surface-water runoff generation. *Soil Use Manage*., 29: 567-575

Pantera , A. *et al.* (2021). Agroforestry and the environment. *Agroforest Syst.* 95, 767–774

Peake, L. R. *et al*. (2022). Priorities for UK soils. *Geoderma Regiona*l, 29, e00512

Piccoli, I. et al. (2022). Examining crop root apparatus traits in a maize-soybean-winter wheat rotation under conservation agriculture management. *European Journal of Agronomy*, 122, 126171, ISSN 1161-0301, https://doi.org/10.1016/j.eja.2020.126171.

Poeplau, C. *et al*. (2024). Cover crops do increase soil organic carbon stocks—A critical comment on Chaplot and Smith (2023). *Glob Change Biol*.; 30, e17128.

POST (2022). *Restoring Agricultural Soils*. POSTNOTE No. 662. January 2022.

Posthumus, H. *et al.* (2013). Costs and benefits of erosion control measures in the UK. *Soil Use Manag*., 31, 16-33.

Powlson, D. S. *et al.* (2012). The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: a case study. *Agri. Ecosyst. Environ*. 146, 23–33.

Pulido-Moncada, M *et al.* (2019). Wheel load, repeated wheeling, and traction effects on subsoil compaction in northern Europe. *Soil Tillage Res*., 186, 300-309

Pun, I. *et al*. (2024). Measuring and modelling the impact of outdoor pigs on soil carbon and nutrient dynamics under a changing climate and different management scenarios. *Soil Use Manage*., 40, e13029

Qin, Z. *et al*. (2023). Assessing long-term impacts of cover crops on soil organic carbon in the central US midwestern agroecosystems. *Global Change Biol.*, 29, 2572–2590.

Reckling, M. *et al*. (2016). A cropping system assessment framework—Evaluating effects of introducing legumes into crop rotations. *Eur. J. Agron*., 76, 186-197

Reed, M. *et al*. (2017). *The effect and impact of LEAF Marque in the delivery of more sustainable farming: a study to understand the added value to farmers*. Project Report. LEAF/CCRI, Gloucester.

Roberts, L. (2020) https://farmwildlife.info/2020/08/08/case-study-reversion-of-arable-land-to-lowland-chalk-grassland/

Roberts, W. *et al*. (2021). Mapping the potential for Payments for Ecosystem Services schemes to improve water quality in agricultural catchments: A multi-criteria approach based on the supply and demand concept. *Water Res*. 206, 117693.

Robinson, C. A. *et al.* (1994). Soil management. In: *Sustainable Agriculture Systems*, 109–134.

Rock on soils (2021) https://www.fas.scot/downloads/rock-on-soils-final-report/ https://www.hutton.ac.uk/news/rock-soils-soil-carbon-development-scottish-farmers

Rothamsted Research (2023). https://www.rothamsted.ac.uk/news/adding-rock-dust-fields-could-absorb-45-co2-needed-meet-net-zero-targets

Rust, N. A. *et al.* (2020) Social capital factors affecting uptake of sustainable soil management practices: a literature review. *Emerald Open Research*, 1, https://doi.org/10.1108/EOR-10-2023-0002.

Sagoo, E. *et al* (2018b). *Optimising sulphur management to maximise oilseed rape yields and farm profitability (OPTI-S*). AHDB project report No. 2160007. *https://projectblue.blob.core.windows.net/media/Default/Research%20Papers/Beef%20&%20Lamb/2160007-Opti-S-Final-Report.pdf*

Sagoo, E. *et al*. (2018b). *Grass and herbal leys farm network*. Final report to AHDB and Defra. https://projectblue.blob.core.windows.net/media/Default/Research%20Papers/Beef%20&%20Lamb/91110083%20-%20Grass%20%20herbal%20ley%20network%20Final%20rpt%20WEB130918.pdf

Sagoo, E. *et al*. (2022). *Sustainable beef systems on arable units*. Final Report for AHDB. https://projectblue.blob.core.windows.net/media/Default/Research%20Papers/Sustainable%20Beef%20Project%20Final%20Report.pdf

Schils, R. L. *et al*. (2022). Permanent grasslands in Europe: Land use change and intensification decrease their multifunctionality. Agriculture, Ecosystems & Environment, 330, 107891.

Schubert, C. (2017). Green nudges: Do they work? Are they ethical?, *Ecological Economics*, 132, 329-342, ISSN 0921-8009, https://doi.org/10.1016/j.ecolecon.2016.11.009.

Schut, A. G. T. *et al*. (2021). Reintegration of crop-livestock systems in Europe: an overview. *Front. Agric. Sci. Eng.,* 8, 111–129.

SEPA (undated). *The Use of Gypsum to Improve Soil Conditions*. https://consultation.sepa.org.uk/operations-portfolio/the-use-of-gypsum-to-improve-soil-conditions/supporting_documents/170529%20Waste%20Gypsum%20Guidance.pdf

Sharma, A. (2020). The Wicked Problem of Diffuse Nutrient Pollution from Agriculture, *J. Environ. Law*, 32, 471–502.

Sharna, S. C. *et al* (2023) A global systematic literature review on sustainable soil management practices (1994–2022). *Soil Use Manage*. 39:1267–1288.

SI (1989). The Sludge (Use in Agriculture) Regulations 1989. UK Statutory Instrument1989 No. 1263.

SI (2006a). The Waste (England and Wales) Regulations 2006. UK Statutory Instrument 2006 No. 937. https://www.legislation.gov.uk/uksi/2006/937/made

SI (2006b). The Water Resources (Abstraction and Impounding) Regulations 2006. UK Statutory Instrument 2006 No. 641. https://www.legislation.gov.uk/uksi/2006/641/contents/made

SI (2015). The Nitrate Pollution Prevention Regulations 2015. UK Statutory Instrument. 2015 No. 668. https://www.legislation.gov.uk/uksi/2016/1190/pdfs/uksi_20161190_en.pdf

SI (2016). The Nitrate Pollution Prevention (Amendment) Regulations 2016. UK Statutory Instrument. 2016 No. 1190. https://www.legislation.gov.uk/uksi/2016/1190/pdfs/uksi_20161190_en.pdf

SI (2018). The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018. UK Statutory Instrument. 2018 No. 151.

Skaalsveen, K. *et al.* (2019) The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: A literature review. *Soil Tillage Res*., 189, 98-109

Skiba, U. *et a*l. (2013). Comparison of soil greenhouse gas fluxes from extensive and intensive grazing in a temperate maritime climate. *Articles*, 10. https://doi.org/10.5194/bg-10-1231-2013

Smith, K. *et al*. (2015). *Soils Research – Evidence Review*. Final report to Defra. http://data.parliament.uk/DepositedPapers/Files/DEP2016-0711/13605_SSPEvidenceReview-Oct15Final.pdf

Smith, P. & Powlson, D. (2007). Sustainability of Soil Management Practices - a Global Perspective. In: *Soil Biological Fertility*. pp.241-254)

Smith, P. (2012). Soils and climate change. *Current Opinion Environ. Sustain*. 4, 539–544.

Smyth, A. J. *et al*. (1993). *FESLM: An international framework for evaluating sustainable land management* (Vol. 73). FAO.

Stagnari, F.*et al*. (2017). Multiple benefits of legumes for agriculture sustainability: an overview. Chem. *Biol. Technol. Agric*. 4, 2 . https://doi.org/10.1186/s40538-016-0085-1

Storr, T. *et al*. (2019). A UK survey of the use and management of cover crops. *Ann. Applied Biol.,* 174, 179-189.

Strauss, V., *et al*. (2023). Sustainable soil management measures: a synthesis of stakeholder recommendations. *Agron. Sustain. Dev.* 43, 17.

Sun, B. *et al.* (2022) Soil carbon and nutrient variations in an arable-ley rotation with organic pig production, *Biol.l Agric. Hortic.*, 38:1, 61-71,

Swoboda, P. (2016). Rock dust as agricultural soil amendment: a review https://unipub.uni-graz.at/obvugrhs/content/titleinfo/1510985/full.pdf

Tallowin, J. R. B. *et al*. (2007). Impact of grazing management on biodiversity of grasslands (Review) *Animal Sci.*, 81, 193 – 198

Techen, A-K, & Helming, K. (2017). Pressures on soil functions from soil management in Germany. A foresight review. *Agron. Sustain. Dev*.37, 64

Ten Damme, L. *et al.* (2019a) The contribution of tyre evolution to the reduction of soil compaction risks. *Soil Tillage Res*., 194, 104283

Ten Damme, L. *et al.* (2019b). Wheel load, repeated wheeling, and traction effects on subsoil compaction in northern Europe. *Soil Tillage Res*., 186, 300-309

Ten Damme, L. *et al.* (2020). Construction of modern wide, low-inflation pressure tyres per se does not affect soil stress. *Soil Tillage Res*., 204, 104708

Tepes, A. *et al*. (2021). Costs and benefits of soil protection and sustainable land management practices in selected European countries: Towards multidisciplinary insights. *Sci. Total Environ*., 756, 143925

Thorsøe, M. *et al*. (2019). Sustainable soil management - Farmers' perspectives on subsoil compaction and the opportunities and barriers for measure. *Land Use Policy*, 86, 427-437.

Townsend, T. J. *et al*. (2015). How do we cultivate in England? Tillage practices in crop production systems. *Soil Use Manage*., 32, 106-117.

Tripney, M. *et al*. (2021). *Review of soil acidity and liming guidance*. AHDB Research Review No. 96

Turpin, N., *et al*. (2017). An assessment of policies affecting Sustainable Soil Management in Europe and selected member states. *Land Use Policy*, 66, 241-249.

Ulrich, A. E. (2019). Cadmium governance in Europe's phosphate fertilizers: Not so fast? *Sci. Total Environ*., 650, 541–545

UN (2016). *Principles for sustainable soil management*. United Nations Global Compact.

Vermang, J. *et al*. (2015). Characterization of Soil Surface Roughness Effects on Runoff and Soil Erosion Rates under Simulated Rainfall. *Soil Sci. Soc. Am. J.*, 79, 903-916.

Wagner, M. *et al.* (2023). Mob grazing: A nature-based solution for British farms producing pasture-fed livestock. *Nature-Based Solutions*, 3, 100054.

Ward, S. *et al*. (2016). Legacy effects of grassland management on soil carbon to depth. *Global Change Biol*., 22, 2929-2938.

Webb, J. *et al* (2014). Ammonia and odour emissions from UK pig farms and nitrogen leaching from outdoor pig production. A review. *Sci Total Environ*., 470-471, 865-875.

Weninger, T. *et al*. (2024). Do we speak one language on the way to sustainable soil management in Europe? A terminology check via an EU-wide survey. *Eur. J. Soil Sci*, 75, e13476

White, C.A. *et al*. (2016*). A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species*. AHDB Research Review No. 90

Whitmore, A. *et al*. (2017). *Improvement of soil structure and crop yield by adding organic matter to soil*. AHDB Project Report 576.

Williams, J. *et al* (2006a). Nitrate leaching and residual soil nitrogen supply following outdoor pig farming *Soil Use Manage*., 21, 245-252.

Williams, J. *et al*. (2006b) Nitrogen losses from outdoor pig farming systems. *Soil Use Manage*., 16, 237-243.

Withers, P. J. *et al*. (2014). Agriculture and Eutrophication: Where Do We Go from Here? *Sustainability*, 6, 5853-5875

Withers, P.J.A. *et al*. (2017) Reducing soil phosphorus fertility brings potential long-term environmental gains: A UK analysis. *Environ. Res. Letters,* 12, 063001

WRAP (2015). DC-Agri; field Experiments for Quality Digestate and Compost in Agriculture – WP1 report, Prepared by Bhogal, A. *et al*. https://wrap.org.uk/sites/default/files/2020-09/WRAP-DC-Agri_Work_Package_1_-_Effects_on_Soil_and_Crop_Quality.pdf

WRAP/EA (2012). *Quality Protocol. Compost*. https://www.gov.uk/government/publications/quality-protocol-for-the-production-and-use-of-compost-from-waste

WRAP/EA (2014). *Quality Protocol. Anaerobic Digestate.* https://www.gov.uk/government/publications/quality-protocol-anaerobic-digestate

Zani, C. F. *et al* (2020). Grazed temporary grass-clover leys in crop rotations can have a positive impact on soil quality under both conventional and organic agricultural systems. *Eur J. Soil Sci*, 72, 1513-1529

Zhao, J. *et al.* (2022). Global systematic review with meta-analysis reveals yield advantage of legume-based rotations and its drivers. *Nat Commun*., 13, 4926.

Zoca, S. & Penn, C. (2017). An important tool with no instruction manual: a review of gypsum use in agriculture. *Adv. Agron*., 144, 1-44

APPENDICES

Appendix 1. Sustainable Soil Management Review Methodology

The literature relating to the definitions, principles, practices and methods of sustainable soil management was reviewed using the search terms shown in Table A1. Similar searches were undertaken to identify any literature relating to the impacts of climate change and land use change on SSM principles and practices (Table A1).

Table A1: Search terms used in preliminary literature review

Preliminary Search Terms	
Definitions and principles	sustainable soil management' AND 'England' sustainable soil management' AND 'UK' "sustainable soil management" AND "England" "sustainable soil management" AND "UK" "sustainable soil management" AND "UK" AND "principles" "sustainable soil management" AND "UK" AND "definition" "sustainable soil management" AND "UK" AND "practices" "sustainable soil management" AND "UK" AND "methods" "sustainable soil management" AND "UK" AND "techniques" "sustainable soil management" AND "UK" AND "threats" "sustainable soil management" AND "UK" AND "soil degradation" "sustainable soil management" AND "UK" AND "soil threats" sustainable soil management UK sustainable soil management England sustainable soil management UK "sustainable soil management"
Climate change and land use change	"sustainable soil management" AND "climate change" AND UK "sustainable soil management" AND "climate change" AND England "sustainable soil management" AND "changing climate" AND UK "sustainable soil management" AND "changing climate" AND England "sustainable soil management" AND "land use change" AND UK "sustainable soil management" AND "land use change" AND England "sustainable soil management" AND "change of land use" AND UK "sustainable soil management" AND "change of land use" AND England "sustainable soil management" AND "changing land use" AND UK "sustainable soil management" AND "change of land use" AND England

All searches were undertaken using Google Scholar and were filtered by year (2015-2023); the preliminary searches were undertaken on 4-6/12/23. As some searches returned many thousands of ‘hits’, the first page of results only was copied into a Google Scholar library folder and download to an Excel spreadsheet for further evaluation.

After removal of duplicates, an initial list of 109 papers was compiled based on an assessment of the relevance of the paper’s title. Following a further review of the paper Abstracts and the country of publication (i.e. would the findings be relevant in an English context), this was refined to 51 papers taken through to the review.

In addition, the Defra, AHDB and BBSRC project databases were searched using the following keywords: Sustainable AND soil AND management. This allowed relevant ongoing or recently completed research projects related to SSM funded in England to be identified and highlighted in the review.

Appendix 2. Quick Scoping Review (QSR) Methodology

A Quick Scoping Review (QSR) was undertaken to address the following research questions:

- Q1. How does the current regulatory framework and government schemes in England relate to the sustainable management of soils?
- Q2. How do current non-government schemes in England relate to the sustainable management of soils?

The evidence from the literature was identified using keyword search terms and strings in Google Scholar, and by following citations from key primary studies. Grey literature/industry papers were located either through searches of industry websites or directly from stakeholder partners or the project team.

Peer-reviewed and grey literature were included in the first stage search and bibliographies searched to ensure a reliable overview of available evidence. The evidence was collated into review summary matrices within an Excel spreadsheet, supported by accompanying evidence tables to provide a clear, fully referenced and transparent information source. A critical appraisal matrix was also included in the QSR matrix to provide confidence scores for the reliability of evidence. The QSR sought to present a fair interpretation of the evidence base, with the maximum number of final papers taken through for critical review limited to 25 papers per question.

The selection and evaluation of literature for the QSR was undertaken as follows:

Relevant bibliometric databases and information sources. A bibliometric source in Google Scholar was used to retrieve peer-reviewed articles and grey literature.
Chronological selection. The literature used was exclusively from 2015 onwards, as per the scope of the project.
Preliminary scoping review. An initial search was undertaken using the search terms in **Table A2** in different combinations. The preliminary literature search returned between 15 and 61,300 article hits for each of the research questions based on key search terms. As such, further refinement of search terms and search strings was undertaken. The QSR attached as an Annex to this report contains the full list of search terms.
Selection of final articles based on critical review. Initial search results returned 86 articles for Q1 and 73 for Q2. Each of these articles was then screened based on the title and abstracts using a RAG approach, where Red (R) represented titles that were 'clearly not relevant', Amber (A) represented titles which were 'uncertain' and would be taken through to the second phase screening and Green (G) were 'clearly relevant' titles. Second phase screening involved reading the abstract or the first paragraph of the 'clearly relevant' and 'uncertain' publications. From this, 25 'score 1' (Green) references were analysed for Q1 and 22 for Q2. These were then checked by another member of the project and, once finalised, were included in the critical review. The critically reviewed literature was then scored based on their Transparency, Appropriateness, Validity, Reliability & Cogency. The scoring principles for these are found in Table A3.
Content Evaluation. Critically reviewed papers scoring highly (>3) were obtained in full and used as the basis for the evaluation and narrative review. The critically reviewed evaluation content was sourced from peer-reviewed articles, grey literature reports and independent studies and reports. Due to the lack of relevant papers identified, particularly around Q2, the most viable 'Amber' papers were reevaluated and included in the review where relevant. Further searches specifically for industry papers were carried out at this stage to ascertain whether the gaps in the academic literature had been addressed in the grey literature.

Evidence matrix. An Excel based spreadsheet matrix was developed to record the full list of evidence reviewed, the RAG ratings for each piece of literature and the critically reviewed relevance and quality scores for the final evaluated pieces of evidence.

Table A2: Example Keywords used in preliminary scoping review of literature

Preliminary Search Terms	
Q1	soil management and pollutants regulations Sustainable Soil Management And England And Policy Sustainable Soil Management And England And Governance soil management and "sustainable farming incentive" and +England soil management and "sustainable farming initiative" and +England
Q2	Soil Association Organic Standards And England And Livestock manure or fertilisers or irrigation efficiency or pest management (as an example of private scheme literature) England AND Sustainable Soil Management And "+voluntary Initiative" Sustainable Soil Management And England And Private Voluntary Schemes England AND Sustainable Soil Management And +Schemes

Table A3: Critical review scoring guide

Criteria	Description (low score)	Score (1 low, 5 high)					Description (high score)
Transparency	Biased literature to serve interests of funding body	1	2	3	4	5	Full disclosure on data, theory and methodology which informs literature
Appropriateness	Irrelevant to Research Questions	1	2	3	4	5	Fully relevant argument that is relevant to Research Questions
Validity	Illogical article that does not provide a sound evidence base	1	2	3	4	5	Logically or factually sound conclusions reached from the primary or secondary evidence discussed
Reliability	Unsubstantiated article	1	2	3	4	5	Provides consistent findings that are accurate and trustworthy
Cogency	Vague and unclear, no clear argument	1	2	3	4	5	Clear, logical argument backed up with robust methodology

Appendix 3. PESTLE Methodology

The elements of the PESTLE analysis were defined as follows:

Political: refers to evidence gathered on policies and regulation from outside of the English legislative context, but which have either influenced the regulation or can be used as a comparator to the legislation. This included:

- Areas where the supranational might have impacted policy, such as the United Nations (UN) Sustainable Development Goals (SDGs).
- Cross-comparisons of literature from the European context.
- Instances where national political events have influenced the regulation, schemes, or uptake for the measures.

Social: refers to evidence associated with participation in voluntary (government and non-government) schemes. This included:

- Non-government voluntary schemes which have requirements around specific SSM measures for the fulfilment of scheme entry.
- Government schemes which provide support and funding for the implementation of the SSM measures
- Attitudinal evidence associated with SSM measures (i.e. evidence that farmers regard the measures as being of value, evidence on the level of uptake, etc).

Legal: refers to the evidence associated with the impact of English regulation on the identified measures. This included:

- Regulations and legislation which farmers must adhere to when implementing specific measures.
- Additional guidance and standards that help support the implementation of the legislation.
- Evidence on the efficacy of the regulations.

The PESTLE framework was first populated with evidence from the QSR. This was then cross referenced and expanded with insights from the project team.

Appendix 4. Case studies

Case Study 1. Dyson Farming, Lincolnshire.

Interview with Dr Tom Storr, Research Agronomist Dyson Farming

Dyson farming has several locations across the country. This case study focuses on their farms in Lincolnshire (3 sites) which are principally arable farms, although livestock (sheep) are being increasingly used to graze cover crops and grass/herbal leys.

Farm details

Location: three farm sites: Carrington (*c*.3300 ha), Leadenhall (*c*.680 ha) and Nocton (*c*.4940 ha). All subject to NVZ regulations

Principal cropping: Arable (including cereals, oilseeds, peas, sugar beet and potatoes); No fixed rotation but follow the principles of:

- Potatoes 1 in 8 years
- Sugar beet 1 in 7 years
- Peas 1 in 6-8 years
- Oilseed rape 1 in 5 years
- Minimising second cereals

Poorly performing land tends to be taken out of production and put into environmental schemes (e.g. Countryside Stewardship or SFI options).

Livestock: *c*.1,000 sheep graze the grassland, herbal leys and cover crops in the arable rotation.

Soil types: range from light heathland soils (2-3% SOM), organic clay loams (35% SOM), sandy loams, silt loams and heavy clay soils (clay @55%)

Accreditations: Red Tractor and LEAF

Soil quality issues on farm

Compaction (due to machinery weight), limited working windows on the heavier soil types, wind erosion on the lighter soil types.

Soil management practices

Cultivations: no fixed cultivation strategy – tailored and adapted to soil conditions. However, they have moved towards reducing the level of ploughing, motivated by a desire to improve their carbon footprint (as a lot of carbon tools take tillage into account). No till (direct drilling) is conducted on some fields/farms but not everywhere, with discs/tine cultivators as well as subsoilers used according to soil conditions.

Residue/stubble management**:** straw is incorporated

Grass leys: used particularly on the heavier soil types to 'rest' a field. These were originally grass clover leys, but SFI options have led to a switch to herbal leys.

Livestock integration: sheep graze cover crops and some 2-year grass leys.

Drainage: An active approach to drainage is taken, renewing drains where required on the heavier soils and fenland locations. Ditches are cleared on a regular basis and drains 'jetted' ahead of high value crops such as potatoes. Mole draining on the heavier soil types occurs every c. 5 years.

Organic material applications: solid & liquid digestates, poultry and pig manures are regularly applied for their nutrient value. Compost is applied to improve soil organic matter levels.

Cover cropping: used before maize and sugar beet crops, but less so ahead of potatoes due to concerns over pest/pathogen carry-over. The initial driver for cover cropping was to help control erosion and retain nitrogen. However, recently they have been used more widely to support sheep grazing and because they can get an SFI payment. They have explored and been successful with catch cropping after vining peas, but not had much success with oversowing grass into maize..

Nutrient Management practices

Crop management software is used for nutrient management planning and record keeping to fulfil Red Tractor requirements. The Farming Rules for Water have motivated the business to invest in low emission spreading equipment for their liquid manures (digestate).

Soil monitoring

Soil mapping is used to suppport variable rate fertiliser (for nitrogen and lime) applications and variable rate seeders (on the heavier soil types). A programme of soil organic matter monitoring commenced in 2016, with sampling conducted every 4 years. The SFI has encouraged increased in field assessments of soil condition, such as visual evaluation of soil structure (VESS), which they use to help produce a soil management plan.

Motivations and incentives

'*Sustainable soil management is all about producing the best crops with the least amount of work to our soils'*

'Good soil means good business'

Accreditation to schemes such as Red Tractor and Leaf Marque have steered many decisions on farm, but SFI has provided the incentivization to do this more formally (e.g. introducing cover crops and herbal leys, producing a soil management plan and regularly monitoring soil condition). However, carbon management and the drive towards getting the business to net zero has also played a part, particularly in stimulating a move away from the plough. Legislation is considered to be unlikely to help drive best practice – changes in practice will be driven more by financial considerations. A key funding gap missing from schemes such as SFI is for drainage installation and maintenance – a problem that has been particularly highlighted this season (2023/2024) given the high winter and spring rainfall.

Case Study 2. GWCT, Leicestershire.

Interview with Dr Alistair Leake, Director of The Allerton Project & Joe Stanley, Head of Sustainable Farming at The Allerton Project.

The Allerton Project is the Game & Wildlife Conservation Trust's (GWCT) research and demonstration farm in Leicestershire which aims to demonstrate and research how to combine productive farming with a thriving natural environment.

Farm details

Location: The Allerton Project, Loddington, Leicestershire (320ha comprising of *c.*255 ha arable & *c.*30 ha grassland); within a Nitrate Vulnerable Zone (NVZ).

Principal cropping: Predominantly arable; including cereals, oilseeds and beans, although more recently they have stopped growing oilseed rape ('*can't control the pests*') and '*struggle to grow beans'*. The rotation is now cereal dominated, both winter and spring sown and includes a 2-year ley followed by winter barley to help with blackgrass control.

Livestock: Uses neighbouring farmers' sheep to graze some permanent grassland, the leys and cover crops.

Soil types: heavy textured soils (silty clay loam/clay loams)

Accreditations: Although The Allerton Project is a LEAF Innovation Centre, the farm isn't LEAF accredited.

Soil quality issues on farm

A key issue for the heavy clay soils on farm is waterlogging and soil compaction. The drainage system is old and cannot cope with the high levels of rainfall now experienced.

Soil management practices

Cultivations: no fixed cultivation strategy – tailored and adapted to soil conditions '*we never slavishly stick to the same system'*. One field on the farm deliberately focuses on conservation agriculture and has been no-till for over 14 years. On this field a 14% increase in topsoil organic matter (SOM) was measured over the first 10-year period, which annual ploughing of part of the field reduced back to pre-no till levels within 3 years. Anecdotally, they have noticed that this field is the one they can work most quickly and travel on the earliest in the season. '*We can be effectively 50% faster when we're direct drilling rather than ploughing, which means that we're getting twice as much crop in while the conditions are good and that's important because a crop that gets away under good conditions will be more resilient against the bad weather later'*

Residue/stubble management: straw and crop residues returned '*we want to leave as much residue as we can in the field to conserve and return organic matter to the soil'*

Grass leys: Herbal leys (supported by Countryside Stewardship, options AB15 and GS4) are used to help control blackgrass and build fertility.

Livestock integration: Uses neighbouring farmers sheep to graze some permanent grassland, the leys and cover crops.'

Drainage: All of the land is drained, although winter 2023/24 has 'exposed some issues' and some drains are due to be renewed. Hedges are regularly coppiced and ditches cleared. The motivation here is to '*get water off the land, but hold it back where it won't impact cropping so it doesn't cause flooding*'

Organic material applications: A 'straw for muck' deal with a neighbouring farmer provides cattle farmyard manure and they have also experimented with more novel applications e.g. biochar, water pre-treatment waste.

Cover cropping: Cover crops are included in the rotation ahead of spring cropping, but the motivation is more ecological (biodiversity) and environmental (nitrogen retention, soil erosion control) rather than for improving SOM. Beetle banks and buffer strips are also a regular feature in fields (supported via Countryside Stewardship) to improve biodiversity.

Nutrient Management

A nutrient management plan is produced every year by the farm manager based on '*what is expedient*' taking into account fertiliser prices and crop potential. Allowance is made for nutrients supplied by organic materials when planning manufactured fertiliser inputs. Soil mineral N (SMN) samples are taken in many fields as a result of project work, which can influence N applications. Fibrophos and gypsum have been used this year to help improve soil structure and tackle a decline in P indices.

Soil monitoring

Soils across the farm are routinely sampled every 5 years, with some fields analysed more frequently and in more detail depending on the research being conducted/demonstrated. Visual soil assessment is used to help guide cultivation choices. There is some concern over the accuracy of soil carbon and organic matter results year on year, particularly if these are used to support carbon payments. Also they feel there is the potential for confusion and considerably variation in the quality of soil monitoring associated within the context of the SFI scheme SAM1 requirement to assess soil and produce a soil management plan '*soil health can be whatever you want it to be*'

Motivations and incentives

'Sustainable soil management is about doing the right operation for the field and crop in question at the right time'

The primary motivation for all decisions made on farm is to have a productive and profitable farming system, looking first for improvements in efficiency and second for environmental improvements. A key driver for the soil management practices adopted across the farm has been climate change, with the farm aiming to build resilience in its soils by introducing practices which aim to enhance soil organic matter (SOM) and improve soil structure. However, they are concerned that climate change has already been sufficiently severe that it has 'wiped out efforts' to improve soils, particularly this season (2023/24) where waterlogging of the heavy clay soils has resulted in flood barriers being washed away and 'earthworms drowned'. Most of the Countryside Stewardship options included on farm are for ecological/biodiversity improvements rather than soils per se. Their current SFI application includes SAM 1 (soil management plan) and NUM1 (nutrient management plan), with sustainable soil management one of the drivers, but 'cash flow' probably the over-riding factor. SFI payments were considered to be too low by just covering income forgone, and not necessarily providing any incentive ‘to go the extra mile’.

Case Study 3. Home Farm, Norfolk

Interview with David Cross, Farm Manager.

Home Farm was a mixed arable, beef and sheep farm that has transitioned over the last few years to become livestock only (2024 was the last year of arable production). All the farm is on rented land. This case study therefore highlights some of the issues tenant farmers face, the motivations for the transition from mixed arable/beef/sheep to livestock farming and how to manage soils for livestock production. David was an AHDB Beef and Lamb Monitor Farmer from 2019-2023.

Farm details

Location: Home Farm, Sedgewood, Norfolk comprising of c. 400 ha of rented land; within a Nitrate Vulnerable Zone (NVZ).

Tenancy agreement: Most of the land that is actively farmed is under an Agricultural Holdings Act tenancy agreement. David also has an annual grazing licence for some permanent grassland and has access to 'free' grazing of some parkland.

Principal cropping: 2024 was the last year of arable cropping on the farm (which used to grow cereals, potatoes and sugar beet). The farm now comprises of mainly grassland (with some fodder beet) – either permanent pasture or multi-species leys

Livestock: Contract reared beef (c. 600 cattle) and sheep. No livestock are carried over winter (no housing requirement).

Soil types: Sandy loam/loamy sands over chalk, with a high pH (8).

Accreditations: Red Tractor (needed for livestock assurance markets)

Soil quality issues on farm

'*We see it all on the farm, particularly soil erosion and compaction'*

Soil management practices

Cultivations: Tried zero till when he had an arable enterprise, but 'couldn't make it work'.

Residue/stubble management: N/A

Grass leys: Herbal leys (previously under Countryside Stewardship option GS4, but now SFI SAM3 'herbal leys'). Includes the following species: perennial ryegrass, timothy and cocksfoot; lucerne, red and white clover; plantain, yarrow, burnet, sheep's parsley. Lucerne and cocksfoot are included for deep rooting in dry seasons.

Livestock integration: Has contract-reared cattle which arrive on farm fully vaccinated, and gets paid on a liveweight gain basis. No calving requirements and limited veterinary bills.

Grazing management: No cutting, only grazing with the aims of keeping the covers long and frequently moving the animals (i.e. on a daily basis) – similar to 'mob-grazing' principles.

Drainage: freely draining soils

Organic material applications: used to sublet to a pig unit, but these were outdoor pigs and caused soil structural damage, so no longer have pigs. Thinking about applying digestate (farm based) to kick start the forage production on newly established leys.

Cover cropping: Tried when had an arable enterprise.

Nutrient Management

Minimal nutrient inputs (no manufactured nitrogen fertiliser is applied).

Soil monitoring

Soils are routinely sampled for nutrient status and pH, including micronutrients. '*We keep a track of everything*'

Motivations and incentives

'*Sustainable soil management is the fundamental crux of why we have changed everything on farm'*

'There is no excuse for doing the right thing if you are making money, however if you're not then it's difficult to think environmentally'.

David embarked on a transition from arable (cereals and sugar beet) to grass (beef and sheep) as margins on his arable enterprise were small. He wanted to improve his soils and reduce input levels (particularly agrochemicals), but couldn't find a way to make it work without compromising yields. '*We tried reduced tillage and cover crops but struggled to make it work….margins are limited for a tenant farmer'*. The mixed enterprise included a profitable sheep flock and as part of the AHDB Monitor Farmer programme he had an economic assessment of various options for the farm (which proved to be key to stimulating the change in farming practice). Gross margins seemed to be greater for his sheep herd than every other enterprise on the farm, except sugar beet. '*Margins aren't great and the soils aren't either, so let's come up with a way to stay in business while we fix them'* Both Countryside Stewardship grants and SFI have been essential to enable this transition away from arable farming, particularly the capital works grants to support purchasing the infrastructure required (fencing, water troughs, tracks). However, now they are in place David believes this new enterprise is the '*only one that works without any subsidies*' for a tenant farmer.