Agricultural Land Management for Public Goods Delivery: iCASP Evidence Review on Soil Health

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Contents

1. Abstract

Maintaining and improving soil health is essential for the future sustainability of agriculture and the delivery of environmental public goods, such as managing flood risk, mitigating climate change and improving water quality. Despite numerous studies indicating that intensive agricultural practices have led to a decline in soil organic matter and an increase in compaction and soil erosion, it is not always clear which management practices or land management interventions are most likely to lead to an improvement in soil health and how this links to the delivery of multiple public goods. There is a need to provide a robust review of the available evidence to support the development of future land-use policies. This report presents the results of a systematic review of the evidence base in the academic literature concerning the impact of ten land management activities on eight soil health indicators that are related to key soil functions that deliver public goods.

2. Introduction

Healthy soils play a crucial role in providing goods and services to society. Among other things, they support agricultural production, urban development, climate change mitigation and flood risk management. But soil is a limited resource and can be lost or degraded by natural processes and human activities. As most soils take many thousands of years to form, they cannot be replaced if they are washed away or polluted. Soil is at risk from human activities. Agriculture, drainage, extraction, application of wastes and urban development are all classed as pressures which can lead to soil degradation such as: accelerated erosion, contamination, acidification, compaction, salinization and loss of soil organic matter and biodiversity (FAO, 2015). All of these threats lower the current and future capacity of the soil to support human life. For example, poor land management practices account for an estimated 970 million tons of soil loss due to erosion each year in Europe and an estimated 24 billion tons worldwide (UNCCD, 2017). In addition to loss of soil productivity, off-site impacts of soil erosion include water quality problems and increased flood risk. Neglecting soil health, therefore, could lead to reduced food security, greater flood risk, and deterioration in water quality. Understanding and knowing how agricultural practices are affecting soil is therefore essential if we want to develop effective land-use policies to protect and improve the health of our soils and ensure that soils are managed sustainably in the future.

Soil health, or quality, can be broadly defined as ‘the capacity of a living soil to function within natural or managed ecosystems, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health’ (Doran, 2002). Soil performs many key functions (Figure 2.1), such as: acting as a medium for plant growth, a reservoir for water, filtering and transforming material added to it, recycling nutrients, storing carbon, and a habitat for organisms. Soil health changes over time; it can be improved or enhanced by land use and management decisions that consider the multiple functions of soil, but has often been degraded by decisions which focus only on short-term crop productivity (Doran, 2002). To improve the health of agricultural soils, and thus their functionality, requires an adjustment in the management of soils that are in a degraded state. These may be suffering from low soil organic matter and/or compaction and erosion, often as a result of long-term arable cropping.

Soil health can be evaluated using specific soil properties. These properties serve as indicators of soil function because it is difficult to measure function directly and observations may be subjective. These indicators can be linked to key soil functions and the delivery of public goods, such as improved water quality, flood alleviation and climate change mitigation, which follow from these functions as shown in Figure 2.1. Soil health cannot be quantified by one soil health indicator; usually a set of indicators are used. The set of indicators shown in Figure 2.1 have well-established causal relationships to soil functions that deliver public goods, and we have focussed on these in this review, whilst acknowledging that there are other soil health indicators, such as microbial activity measures, which were not included within our scope.

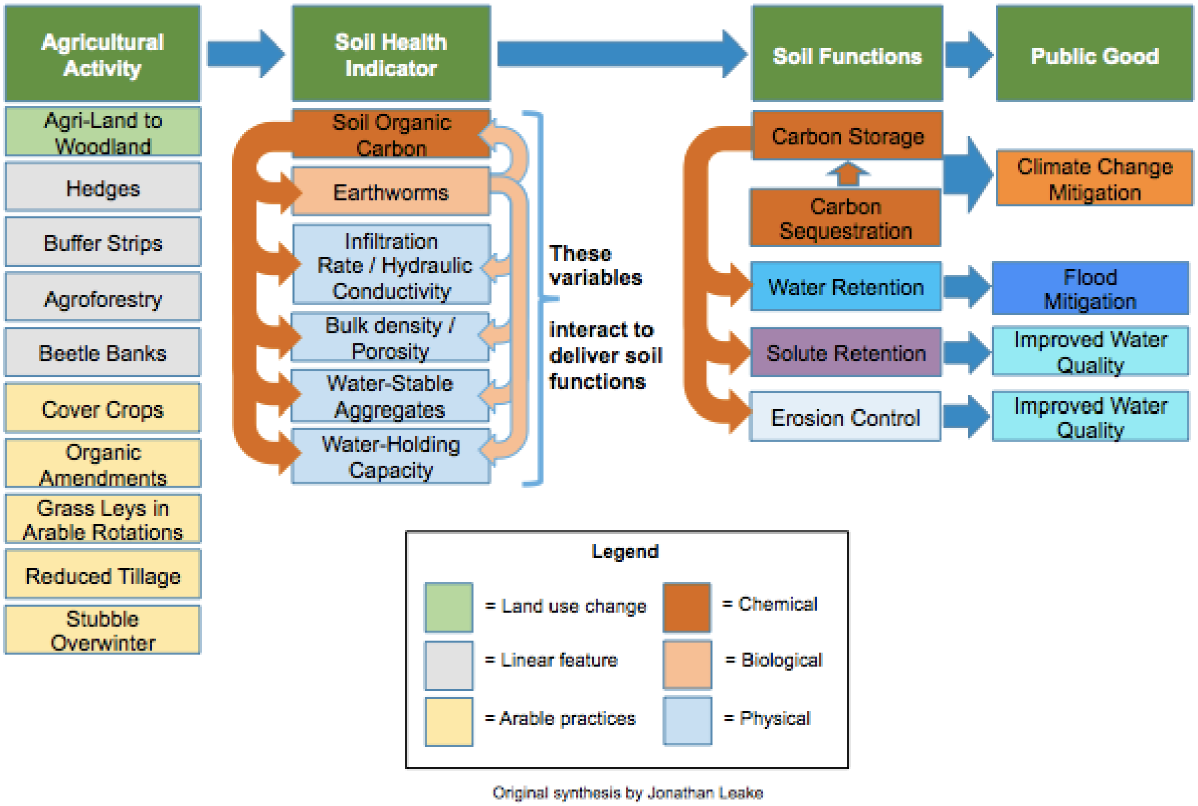


Figure 2.1: Links between a set of core soil health indicators used in this review, soil functions and delivery of some public goods

As the UK leaves the EU, increasing attention is being paid to the future design of national environment policy. Following the recent publication of the 25 Year Environment Plan and England's first Agriculture Bill for over 70 years, the devolved administrations are consulting on and developing their own policies and strategies. There is a unique opportunity for research evidence to shape policy and deliver more effective outcomes than are currently possible. The UK has a rich evidence-base to draw on, and this is the first attempt to synthesise research on soil health to inform post-Brexit environmental policy.

In England's Agriculture Bill and the consultations run by each of the devolved administrations, proposals are made to replace the current subsidy system of 'Direct Payments' to farmers, which is based on the total area of land farmed, with a system based on "public money for public goods". In England, new Environmental Land Management schemes (ELMS) are proposed to reward farmers for undertaking environmental measures that assist in the delivery of public goods. In the new ELMS, farmers will be incentivised to pursue certain farming practices in order to maintain or improve soil health and thus improve the delivery of multiple public goods; this will be accomplished via payments because it is acknowledged that these practices can incur extra costs and/or lead to a reduction in crop yield and therefore a loss of income. The Agriculture Bill now provides an important opportunity for change, but the exact delivery mechanisms of the future ELMS are yet to be finalised.

Although increasing numbers of current best management practices (BMPs) and land management interventions have been studied and implemented globally, including in the UK, via a range of agri-environment schemes (AES), they have usually been designed with delivery of one public good in mind, most commonly improvement in farmland biodiversity or water quality. There have been many reviews and meta-analyses examining their effectiveness (e.g. Liu et al., 2017; Batary et al., 2015; Kay et al 2009). Most, but not all, of which demonstrate general increases in farmland biodiversity or improvements in water quality in response to AES or BMPs. In comparison, few studies have reported the impact of BMPs and AES on soil health. This may partly reflect the fact that soil health cannot be measured directly, but is quantified via a set of soil health indicators. Thus it is currently difficult to evaluate how BMPs and AES affect soil health and help deliver public goods. Within this context, there is an urgent need to provide a robust systematic review of the available evidence in the academic literature on the impact of BMPs and AES options on soil health in order to identify further areas for research to support the development of future land-use policies. This report describes the methodology and the results of a systematic review that investigated the impact of ten land management practices on eight soil health indicators which control key soil functions and are linked to the delivery of improving soil health.

3. Methodology

3.1 Selection of land management activities/interventions

To identify which land management activities to review, we looked at the uptake of options in the Countryside Stewardship Scheme (CSS) in England. The scheme offers over 200 different options, supplements and capital items for farmers to choose from with the aim of achieving simple and effective environmental benefits. As of May 2018, 40% of uptake was for just three options: management of hedgerows, 4-6m buffer strips in arable systems and low input grasslands. Based on a preliminary review and in consultation with the stakeholder steering and academic advisory groups, it was decided that ten land management practices should be selected for a detailed review. Our prioritisation process started by considering all CSS options that had greater than 20 contracts with farmers (64) and selecting the subset that were related to soil health (42). Each member of the stakeholder steering and academic advisory groups was then asked to rank the top ten land management practices/interventions that they wanted to be reviewed. The collated rankings were used to select the following ten land management practices for inclusion within the review:

1) Agroforestry
2) Beetle banks
3) Buffer strips
4) Cover crops
5) Grass leys in arable rotations
6) Hedges
7) Land use change (conversion of agricultural land to woodland)
8) Organic amendments
9) Stubble over winter
10) Tillage practices

3.2 Selection of soil health indicators

The criteria for selecting a set of soil health indicators relates mainly to their utility in defining soil functions and in integrating physical, chemical, and biological properties; their sensitivity to management and climatic variations; and their accessibility and utility to agricultural specialists, conservationists, and policy makers. Indicators can be assessed by qualitative and/or quantitative techniques. A qualitative assessment is the determination of the nature of an indicator. A quantitative assessment is the accurate measurement of an indicator. For example, a qualitative assessment of infiltration would be the observation of excessive runoff water from a field. A quantitative assessment would measure the infiltration rate. We chose eight indicators (Table 3.1) that relate to the soil functions of (i) carbon cycling and storage, (ii) water movement, storage and availability and (iii) retention and transport of solutes (Table 3.1), as these functions link to the delivery of climate change mitigation, flood mitigation and improved water quality (Figure 2.1). Definitions of these soil indicators and how they relate to soil functions can be found in Appendix 1.

Table 3.1 Relationship between soil indicator and soil function

Soil health indicator	**Soil function**
Soil organic carbon	Carbon storage
Infiltration capacity, hydraulic conductivity, porosity, bulk density	Water movement
Water holding capacity	Water storage and availability
Water stable aggregates	Retention and transport of water and solutes, soil erosion
Number of earthworms	Water and solute movement, carbon cycling and storage

3.3 Systematic evidence review

This review only considered peer-reviewed literature on the assumption that the peer review process acts as a quality control across all studies. The review focused on the impact of ten land management practices on soil health indicators but not the delivery of public goods directly, as very few studies have attempted to do this. The review did not carry out independent quality assessment of each study (beyond the peer-review process). This review distinguishes between the papers identified through the screening process (Table 3.3), and the sites identified in each paper. The numbers of papers and study sites reported in the review can differ from each other. Definitions of each are provided below and it is important to bear these in mind when reading this report.

Paper - This refers to an individual publication (in this case from the peer-reviewed literature) identified through searching online databases. Each paper can be identified by a reference and those included in the analysis of this review are listed in the reference list.

Study site - A single paper can contain information from more than one study site each with different characteristics. For example, one paper may compare the results of one experiment at one study site with the results of another experiment at another study site. Each experiment is treated as separate study site.

A systematic approach, as set out by the CEE (Collaboration for Environmental Evidence, 2013), was adopted and the Population, Intervention, Comparison and Outcome (PICO) framework was used to structure the elements of the review (Table 3.2).

Table 3.2: Elements of the review in the PICO framework.

Population	**Intervention**	**Comparison**	**Outcome** (soil health indicator)
Catchment, watershed, site, field, plot	Agroforestry, beetle banks, buffer strips, conservation tillage, conversion of arable/grassland to woodland, cover crops, hedges, leys in arable rotation, addition of organic amendment to arable land, and stubble overwinter.	Paired treatment versus control studies, before and after treatment studies	Soil organic carbon, bulk density, porosity, infiltration capacity, earthworms, water stable aggregates, hydraulic conductivity, water holding capacity

Boolean operators 'AND' and 'OR' were used to combine the search terms into text strings used to search for research articles published between January 1900 and 9th July 2018 and available in Web of Science database (see Appendix 2), which is regarded as one of the most comprehensive and robust electronic databases of peer reviewed journals. Separate searches were conducted for each intervention excluding the linear features (i.e. buffer strips, beetle banks, hedges and agroforestry). A single search was conducted for the linear features using the search terms developed for a systematic review of vegetated filter strips (Appendix 2; Haddaway et al., 2018). The search was limited to research articles published in English.

Articles provided by academic advisors were also added to the articles obtained from the Web of Science database. A limitation of using Web of Science is that it does not pick up publications in books and reports (such as those carried out for Defra and NE).

The articles obtained from the Web of Science database and those provided by academic advisors were screened based on the following criteria:

1. The study reported the effects of one or more selected land management activities on at least one soil health indicator;
2. The study was carried out in countries from the temperate zone.

The screening of all articles was done in two stages. The first stage involved title and abstract screening, whereas the second stage was a full text screening. It was found that studies that investigated the effects of overwinter stubble on soils were mostly carried out in Australia; hence the Australian overwinter stubble studies were included for review. In addition, review articles or meta-analyses that included studies from other climactic zones were included in this review. Articles that did not meet these criteria were excluded from those selected for review. A total of 240 articles were selected after a thorough screening of 8017 articles (Table 3.3). In addition, the following articles were excluded:

1. Individual agroforestry-soil organic carbon (SOC) studies already considered in previous reviews or meta-analysis. This is because four recent (2014 – 2018) global reviews on the effects of agroforestry on SOC were available and selected for this review. These four reviews synthesized the results of individual agroforestry-SOC studies globally.
2. Studies that focused only on the reduction of sediments or pollutants such as nitrate and phosphate in surface runoff without any measurement of soil health indicators such as infiltration capacity and hydraulic conductivity.
3. Studies on natural succession of woodland, bioenergy crops, mountain forests, and agroforestry when considering the land use change of agricultural land to woodland.

Table 3.3: The number of articles obtained from database search and the number reviewed.

Intervention		**Number of articles yielded by database search**	**Number of articles provided by advisory team**	**Number of articles included for review after screening**
Conservation tillage		2890	2	90
Conversion of arable/grassland to woodland		1177	0	25
Cover crops		742	0	32
Introducing leys into arable rotation		153	0	15
Organic amendment to arable land		1083	0	26
Stubble overwinter		310	0	10
Linear features	Agroforestry	1654	6	7
	Beetle banks			0
	Buffer strips			23
	Hedges			12

Quantitative and qualitative data were extracted from the articles that were selected for review. Information about the study location, mean annual precipitation and temperature, soil type, depth of soil sampled, land use, specific interventions, study design, scale and duration of study, soil health indicators measured, method of data collection, and effect of interventions on target soil health indicator were extracted from the selected articles. The statements (i.e. the finding in relation to the influence on each soil health indicator) were categorised according to their reported statistically significant (p<0.05) effect on each soil health indicator as either increase, decrease or no change. Where no p values were reported, the qualitative description of the significance of effects reported in the papers was used.
All subsequent analysis was carried out on the statements, using the vote account method to assess the numbers of statements reporting a particular influence on each soil health indicator. While we recognise the limitations of a vote account method (Stewart, 2010), it is the most suitable for the data collected in this review. An alternative to the vote-counting approach is

meta-analysis. In order to carry out meta-analysis, papers need to include information on measures of variation and sample size. If only papers containing this additional information were included, the available database would be further constrained, and the database for most agricultural practices was already small (Table 3.3). For each intervention and soil health indicator, the most frequently reported category was considered, the balance of evidence or simply the overall effect. Where data reported in the reviewed studies were collected from field experiments with well-defined controls or a meta-analysis of data from such field experiments, the results reported were considered as strong evidence for the effects of the intervention on soil health. The conclusions from narrative reviews without meta-analysis of data were considered as moderate evidence.

4. Results

4.1 Summary of literature reviewed

As a result of the screening process outlined in section 3.3, 240 papers were included in this review and data extraction was carried out on each. Only 17 of these papers were from the UK, highlighting how limited the information available is on how some of the most commonly promoted agricultural practices improve soil health in the UK. Across the majority of land management activities, the available database on soil health is limited (Figure 4.1). Tillage had the most studies (90) followed by cover crops (32), with the other interventions all having less than 30 studies. No suitable soil health impact studies were found for beetle banks. The majority (92%) of the papers used a control versus treatment experimental approach, where the control is used as a baseline and is identical in characteristics (e.g. soil type, climate) to the treatment study site(s) which receive the experimental manipulation (i.e. the land management practice). The most commonly reported soil health indicators were soil organic carbon and bulk density (Figure 4.2). Aggregate stability was reported in 56% of the papers and number of earthworms in 34% of papers. Hydrological properties (infiltration rate and/or hydraulic conductivity) were reported in 34% of papers. Very few studies that reported the impact of land management activity on soil health indicators also measured the impact on crop yield; those that did were mainly in relation to tillage practice.

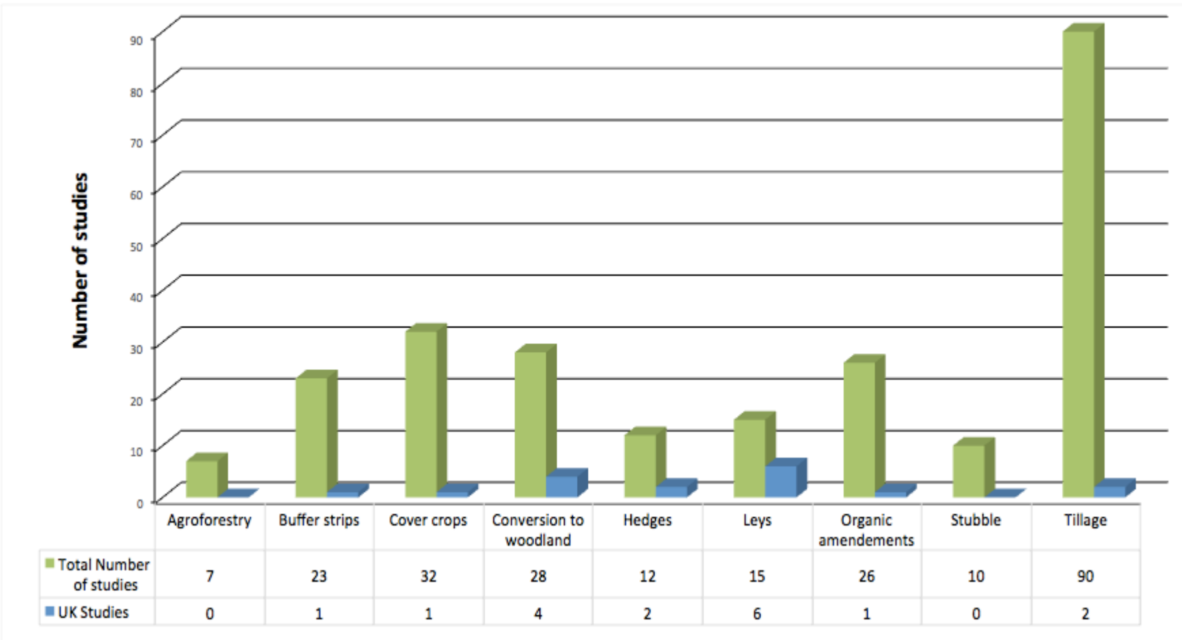


Figure 4.1: Number of papers reviewed for each land management activity

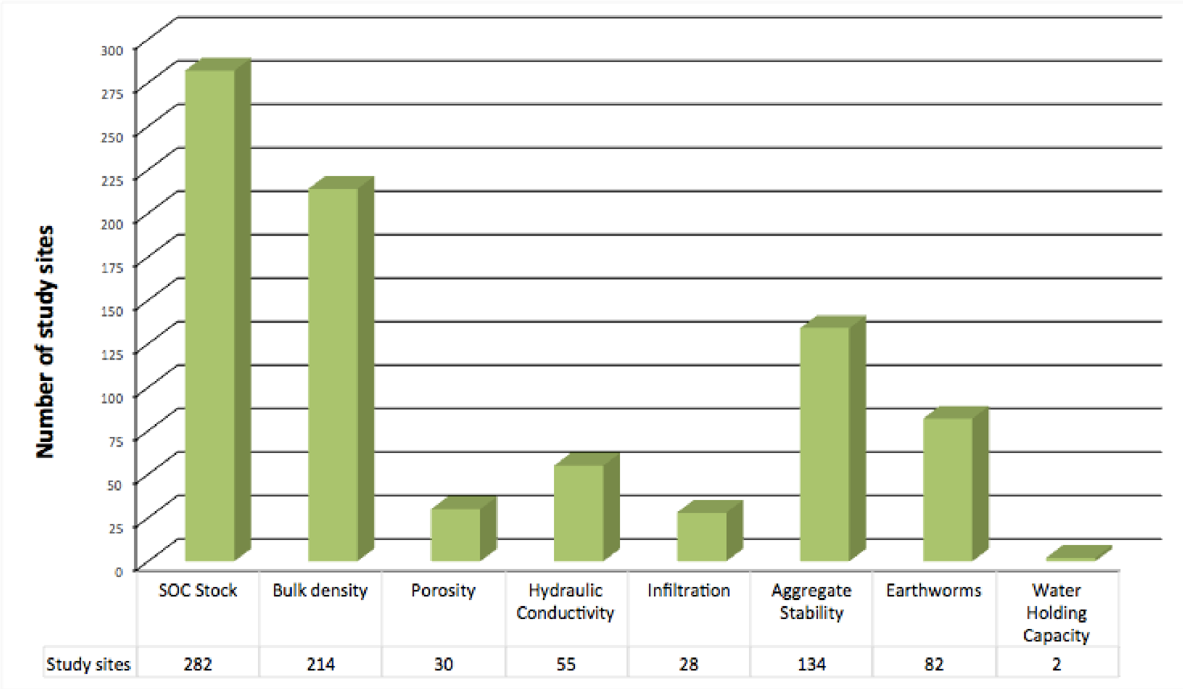


Figure 4.2: Number of studies reporting each soil health indicator

It is interesting to note that only 14 papers reported soil health indicators in soil below 30 cm in depth; most of these were related to tree planting. Therefore a major gap in knowledge is how soil properties and soil functions at depth respond to changes in land management. For example, globally, soil stores 2400 Gt of carbon, two-thirds of which is at > 20 cm depth. In addition, several studies have observed that while changes in tillage practice from conventional and deep ploughing to zero and minimal tillage result in an increase in soil organic carbon (SOC) content in the surface 30 cm (e.g. Sun et al., 2011), they find that over a greater depth (e.g. 60 to 100 cm) the SOC contents were similar for all tillage practices. This suggests that tillage practice influences the distribution of soil carbon in the soil profile, but not the sequestration of carbon in the whole soil profile and thus does not contribute to climate change mitigation, even if there are functional benefits for soil hydrological function. In addition, the majority of studies (81%) were carried out at the field scale (Figure 4.3). It is important, therefore, that we identify how public goods delivery at the landscape scale can be measured, through e.g. large scale landscape networks, and/or modelling approaches. Finally, most studies (57%) looked at the short-term change in soil health indicators, with only 19% of studies considering the longer term (>20 year) impact. This is important, as quantifying the impact of land use change on soil organic carbon (SOC) stock can take a long time because one of the difficulties in attempting to assess changes in SOC is that the magnitude of any change tends to be very small in relation to the variation.

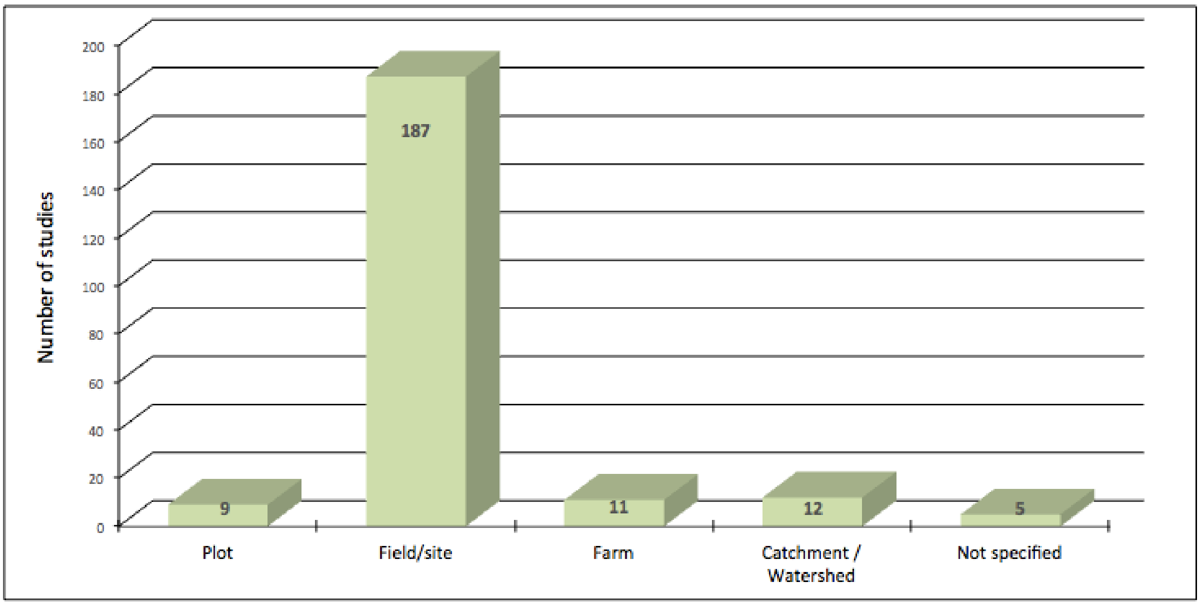


Figure 4.3: Scale at which each study was carried out.

4.2 Results by land management activity

As described in Section 3.3, the main analyses carried out in this review consider the number of statements regarding the influence of land management activity on soil health indicators. The results of those analyses are presented in the following sections.

4.2.1 Agroforestry

Definition: Agroforestry is the practice of deliberately growing trees in combination with arable crops or pasture on the same piece of land. Agroforestry is seen as a sustainable management practice which might deliver additional ecosystem services and improve soil fertility.

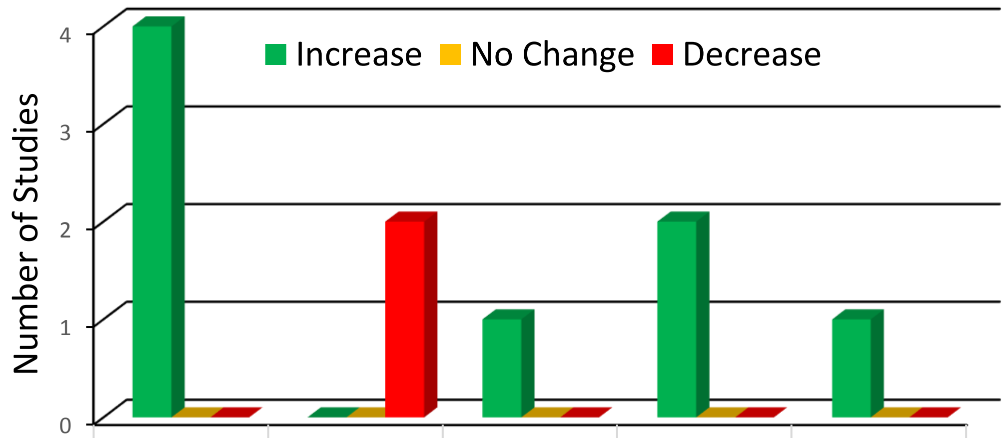
Key Messages

- There is strong evidence that agroforestry increases the soil's capacity to store organic carbon; however, most studies were carried out in the tropics.
- Agroforestry may improve other soil health indicators; reduced bulk density, increased hydraulic conductivity, and increased earthworm population were all reported in the literature. However, more data are urgently needed from temperate agroforestry systems to make this a reliable conclusion.

Review Findings

Agroforestry resulted in a significant increase in soil organic carbon (SOC) storage (Figure 4.1) after 4 to 25 years of establishment. The effect of agroforestry on SOC storage reported here was based on the results of over 100 field experiments across the globe that have been summarised in four review papers (De Stefano and Jacobson, 2018; Dollinger and Jose, 2018; Kim et al., 2016; Lorenz and Lal, 2014). Although the majority of these studies (over 80%) were from the tropics and subtropics, the results provided strong evidence for the agroforestry-induced increase in SOC storage. Lorenz and Lal (2014) explained that agroforestry systems have a higher potential for carbon sequestration than the treeless arable or pasture lands because trees have extensive root systems with high carbon deposition within the soil profile. Similarly, there is efficient use of resources such as nutrients in agroforestry systems compared to monocultures. For example, tree roots recover nutrients from below the crop and pasture species' rooting zone and return the nutrients to the soil surface as litter. This promotes biomass production and carbon input to the soil (Lorenz and Lal, 2014). However, Oelbermann et al. (2014) reported that in temperate zones, agroforestry had to be established for more than 10 years in order to see an increase in soil carbon due to lower turnover rates than in the tropics. In addition, it is unclear whether planting trees in pastures in the temperate zone has the same benefit for SOC stock as planting trees in arable fields (see Section 4.2.4; Upson et al., 2016).

Agroforestry also resulted in a significant increase in total porosity, hydraulic conductivity and earthworm population, and a significant decrease in soil bulk density (which reflects the increasing porosity). However, the evidence for these effects was only available from three studies (Figure 4.1). See Appendix 3 for further information.



	SOC Stock	* Bulk density	Porosity	Hydraulic Conductivity	Earthworms
Increase	4	0	1	2	1
No Change	0	0	0	0	0
Decrease	0	2	0	0	0

* Decreases in these indicators improve soil health

Strength of Evidence: Strong

Figure 4.1: Summary of Findings for Agroforestry (n=7 studies)

Strength of evidence

Strong: All data, except conclusions from two narrative review papers, were based on results of field experiments.

Gaps in knowledge

- While long-established in sub-tropical and tropical climates, uptake of agroforestry in temperate agricultural systems has been slow, particularly in the UK (Woodlands Trust, 2018). There is an urgent need for better understanding of how planting trees in temperate agricultural systems impacts on soil health indicators, and how this is affected by choice of species, or species mixtures.

- Very few studies have investigated the effects of agroforestry on physical components of soil health such as bulk density, hydraulic conductivity and infiltration, which are important for regulating water flow and quality.
- There is currently insufficient information on the effects of agroforestry on soil biota, such as earthworms.

4.2.2 Buffer strips

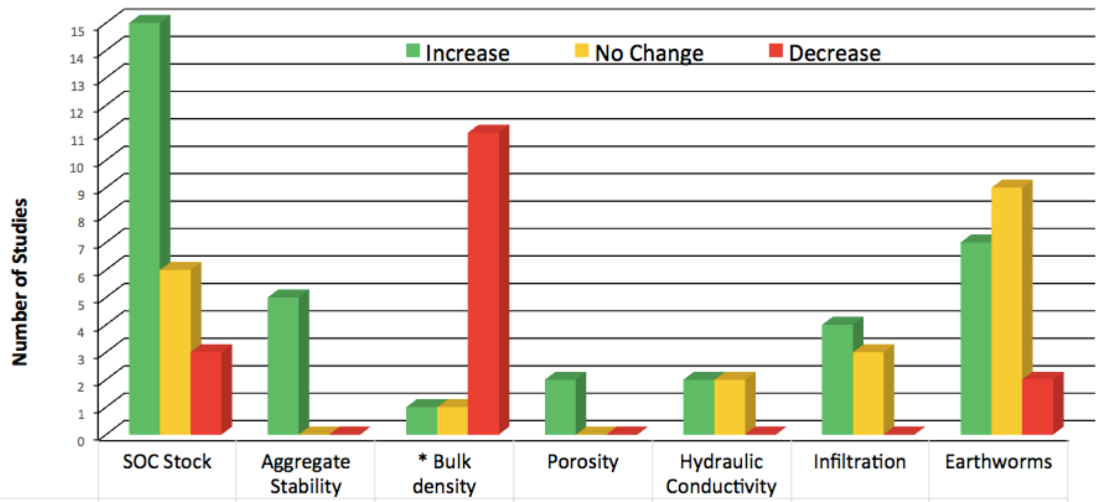
Definition: A buffer strip is a strip of permanent vegetation, ranging in width from a few meters to 10s of metres, in or around the edges of fields and often next to water courses. The strip may include trees, grasses (most common) and wetland plants and is managed separately from the rest of the field. Often cited is the riparian buffer strip used primarily to prevent pollution from agricultural run-off entering water courses. Additional known benefits from buffer strips include: providing habitat for wildlife, forming corridors between habitats, stabilising channels, and, if fenced, preventing stock access to waterways. Other types of linear vegetated strips such as field margins, hedges, shelter belts and beetle banks, are not included in this definition of a buffer strip. Hedges are considered separately (see section 4.2.5)

Key Message

- The soil health within buffer strips established around or within arable fields is improved compared to the rest of the arable field. In particular, soil organic carbon, bulk density and aggregate stability are improved.

Review Findings

Overall, the balance of available evidence suggests that establishing buffer strips in arable fields helps to improve soil health in the strip relative to the rest of the field. It does not necessarily mean that soil within the whole of the field is enhanced. However, one study comparing earthworm populations in fields with and without buffers found more earthworms in the field with buffer strips (Hof and Bright, 2010). Of the 23 studies reviewed, 19 compared the buffer strip soil with the adjacent arable soil and found that the buffer strips had significantly higher soil organic carbon (SOC) storage, aggregate stability, water holding capacity and infiltration. Soils within buffer strips also had significantly lower bulk density than in arable fields. Only four studies compared the soils of buffer strips in or around pasture fields, and variable results were reported. For example, at some sites, SOC in the buffer strip was higher than in the pasture, whereas at other sites, the reverse was the case. For earthworm numbers and infiltration rates the evidence was more varied; a similar number of studies reported a significant increase and no significant change (Figure 4.2) in the buffer strip relative to the field. This suggests that other factors, such as soil moisture content at time of sampling, and soil and vegetation type, are important in controlling earthworm numbers and infiltration rate. See Appendix 4 for further information.



	SOC Stock	Aggregate Stability	* Bulk density	Porosity	Hydraulic Conductivity	Infiltration	Earthworms
Increase	15	5	1	2	2	4	7
No Change	6	0	1	0	2	3	9
Decrease	3	0	11	0	0	0	2

* Decreases in these indicators improve soil health

Strength of Evidence: Strong

Figure 4.2: Summary of findings for Buffer Strips (n=23 studies)

Strength of evidence

Strong: All data were collected from field experiments except one modelling study and one review.

Gaps in knowledge

- Very few studies (four) have compared soil health indicators of buffer strips in livestock systems.
- Although there is an indication of improved soil health in arable fields with buffer strips compared to those without buffer strips, more empirical evidence is needed to verify this.
- What is grown in the buffer strip could influence the delivery of soil-based environmental goods and services. To date, the species choices for buffer strips have focussed on providing pollen and nectar for insects. We need to know more about which species are best to plant in buffer strips for multiple benefits and how they should be managed; this scientific evidence is needed for policy development.

4.2.3 Cover Crops

Definition: In temperate climates, cover crops are usually grown in the period between harvest and re-establishment of the next crop. The use of cover crops has long been promoted for reducing soil erosion and nitrate leaching, and suppressing some pests and diseases.

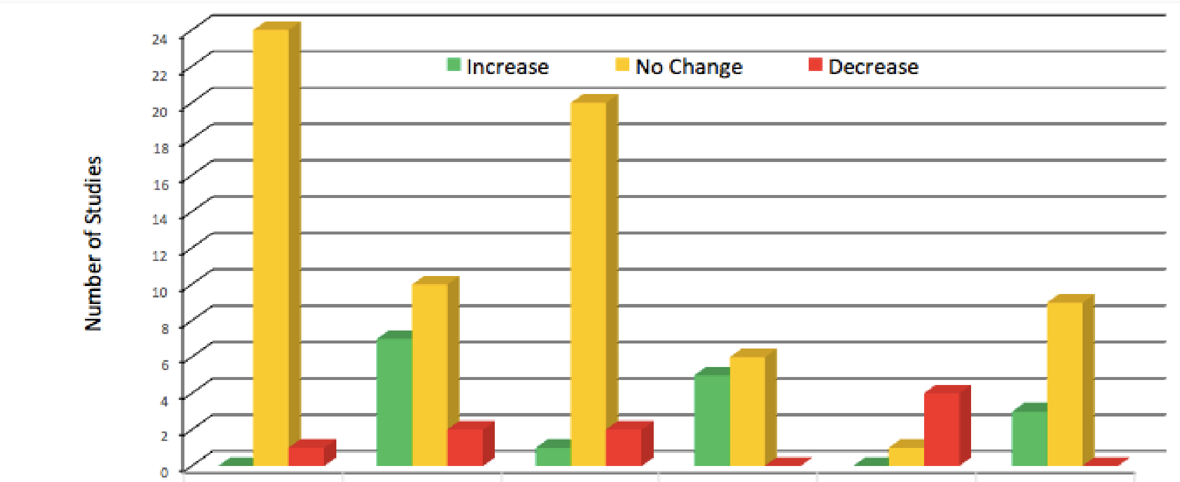
Key Messages

- Cover crops maintain soil health in the short term and may improve soil health in the long term (greater than 10 years).
- The effectiveness of cover crops in improving soil health depends on the species of cover crop, as some produce more biomass than others, the crop rotation, and the duration of cover crop management.

Review Findings

Different groups of cover crops including cereals and grasses (e.g. rye, wheat, oat and fescue), legumes (e.g. clover, pea and vetch) and brassicas (e.g. oil radish and mustard) were identified, amongst others (see Appendix 5). The effects of these single species cover crops on soil health indicators, particularly soil organic carbon (SOC) storage, soil aggregate stability and bulk density varied widely, with studies reporting no significant effect, an increase and a decrease (see Figure 4.3 and Appendix 5). This is consistent with the findings of a previous review by White et al. (2016) who reported that the effect of cover crops on soil organic matter was variable. This variation is due to a number of factors, including differences in soil textures, crop rotation, cover crop species, weather during the study period, cover crop success rate, fertilizer rate, planting date, and whether and how the cover crop was incorporated into the soil. For example, the duration of cover crop management in the studies reviewed ranged from 1 to 54 years. This might have resulted in large differences in the level of biomass accumulation and organic matter inputs to the soil, and hence the variability in the SOC storage (White et al., 2016). Differences in cover crop species are also an important determinant of the net effect of cover crops on soil health. For example, among the legume cover crops, clover and lentil increased SOC storage whereas vetch and pea had no significant effect. White et al. (2016) explained that different legume cover crops vary in their ability to influence soil properties and functions due partly to differences in the level of biomass production.

Although the majority of studies observed no significant effects of cover crops on the soil health indicators reviewed, in those where a significant effect was observed, it was positive for SOC, aggregate stability, porosity and earthworms. Hydraulic conductivity was the only soil health parameter that was significantly reduced. The non-significant effects of cover crops on most of the soil health parameters, especially SOC, could be attributed to the short term duration of the studies reviewed. Most of the studies (84%) reported less than ten years of cover crop management, and the crops themselves are only grown over winter when temperatures and light are often strongly limiting growth. Beehler et al. (2017) suggested that the effects of cover crops on SOC storage might not be detectable until after 7 to 10 years. However, there is no indication in this review that cover crops will cause significant reductions in SOC storage, aggregate stability, and earthworm population even in the short term. Cover crops also help to reduce soil erosion (Panagos et al., 2015) which in turn ensures that the loss of SOC from the field is minimized. The results of this review therefore suggest that cover crops tend to maintain soil health in the short term and may improve soil health in the long term; only five studies investigated impacts where cover crops had been used for a period of greater than ten years. See Appendix 5 for further information.



	SOC Stock	Aggregate Stability	* Bulk density	Porosity	Hydraulic Conductivity	Earthworms
Increase	0	7	1	5	0	3
No Change	24	10	20	6	1	9
Decrease	1	2	2	0	4	0

* Decreases in these indicators improve soil health

Strength of Evidence: Strong

Figure 4.3: Summary of Findings for Cover Crops (n=32 studies)

Strength of evidence

Strong: Data were based on results of field experiments.

Gaps in evidence

- There is limited information on the effects of cover crops on soil health indicators in UK arable systems in the academic literature; only one study in the literature was from the UK.
- All of the studies reviewed the impact of single species on soil health indicators, but UK farmers are now using mixtures of species (e.g. mustards, radishes and grasses) in their cover crop and these may prove more effective than a single species in their ability to improve soil health and deliver public goods. However, no published data are currently available.

4.2.4 Land use change – agricultural land to woodland

Definition: In order to feed a growing population, land cover or land-use change (conversion of natural land to managed land) has occurred, which is known to have led to a decline in soil organic carbon and change in soil properties. Converting degraded and low-productivity agricultural land back to woodland/forest is therefore seen as a way to restore ecosystem function and, in particular, to mitigate climate change.

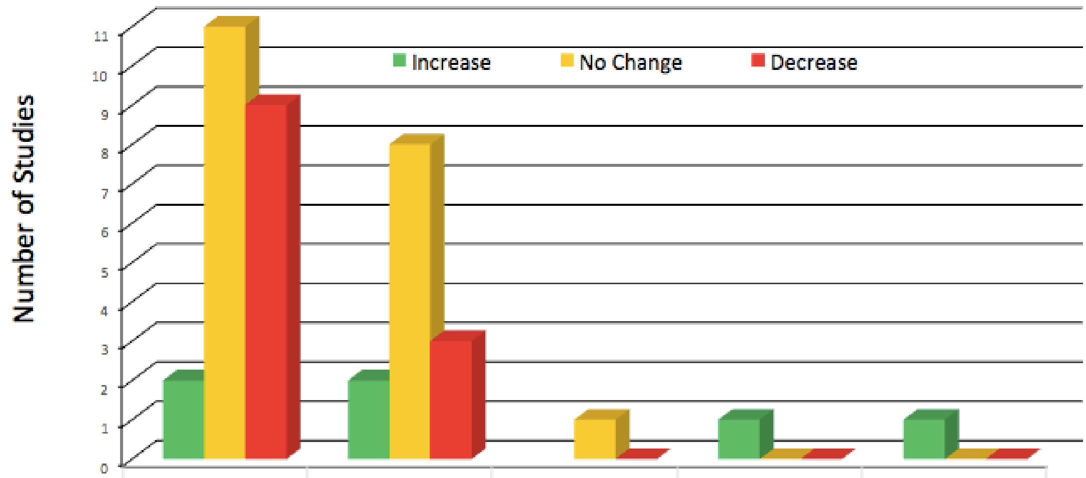
Key Messages

- There is strong evidence that converting grassland to woodland has no significant effect on soil organic carbon stock over the first 20 years.
- There is strong evidence that converting arable land to woodland significantly increases soil carbon stock.

Review Findings

Most of the reviewed studies (64%) reported the effects on soil health indicators of converting agricultural land to conifer plantation. More than half of the reviewed studies reported that converting grasslands to woodland had no significant effect on soil organic carbon (SOC), bulk density and water stable aggregates. This may be due to a relatively large initial carbon in the grasslands prior to their conversion to woodlands. It is also possible that more time is needed for any change in SOC to be detected in the woodlands, as most of the studies were less than 20 years old. Converting arable lands to woodlands resulted in a significant increase in SOC storage. This is because in arable lands, there is increased mineralization of soil organic matter and lower input of carbon to the soil (Hermle et al., 2008). Conversely, woodlands tend to accumulate litter, which increases the stock of organic carbon in the soil (Poulton et al., 2003). Other soil health parameters such as total porosity, infiltration and hydraulic conductivity were significantly increased when arable/grasslands were converted to woodlands (Figure 4.4a and 4.4b). However, compared with most broadleaved trees, we know that coniferous trees and their litter acidify the soil over time, which can lead to changes in other soil processes such as carbon cycling (Vanguelova et al., 2001). Therefore, it is important to consider which tree species or mixtures of species are best for a given site. In addition, forest development influences soil properties over time, which is also highly dependent on the initial choice of tree species, density of planting and the forest management practiced during the forest life cycle (Vanguelova et al., 2011)

Our results agree with those of Poeplau et al. (2011) who reported for sites in the temperate zone that (i) afforestation on former cropland was a sink of carbon (SOC storage increased), (ii) there was no SOC sink following afforestation of grasslands, and (iii) ninety percent of the observations in the meta-analysis originated from coniferous afforestation. Therefore, the influence of planted temperate deciduous tree species on the SOC dynamics could not be evaluated. See Appendix 6 for further information.



	SOC Stock	* Bulk density	Aggregate Stability	Hydraulic Conductivity	Infiltration
Increase	2	2		1	1
No Change	11	8	1	0	0
Decrease	9	3	0	0	0

* Decreases in these indicators improve soil health

Strength of Evidence: Strong

Figure 4.4a: Summary of Findings for Land use change – grassland to woodland (n=18 studies)

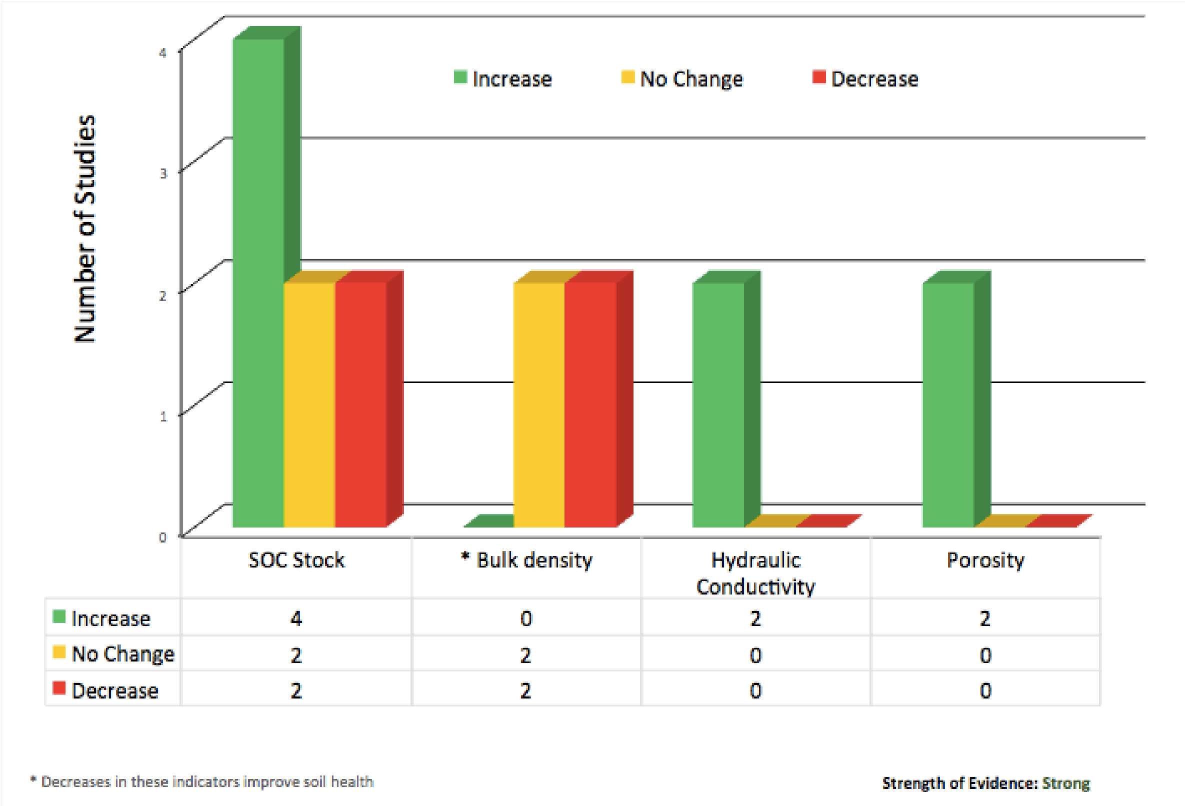


Figure 4.4b: Summary of Findings for Land use change – arable land to woodland (n=9 studies)

Strength of evidence

Strong: All data, except one modelling study, were based on results of field experiments.

Gap in evidence

- There is limited information on the impacts on soil health of planting agricultural land with deciduous tree species in the temperate zone.

4.2.5 Hedges

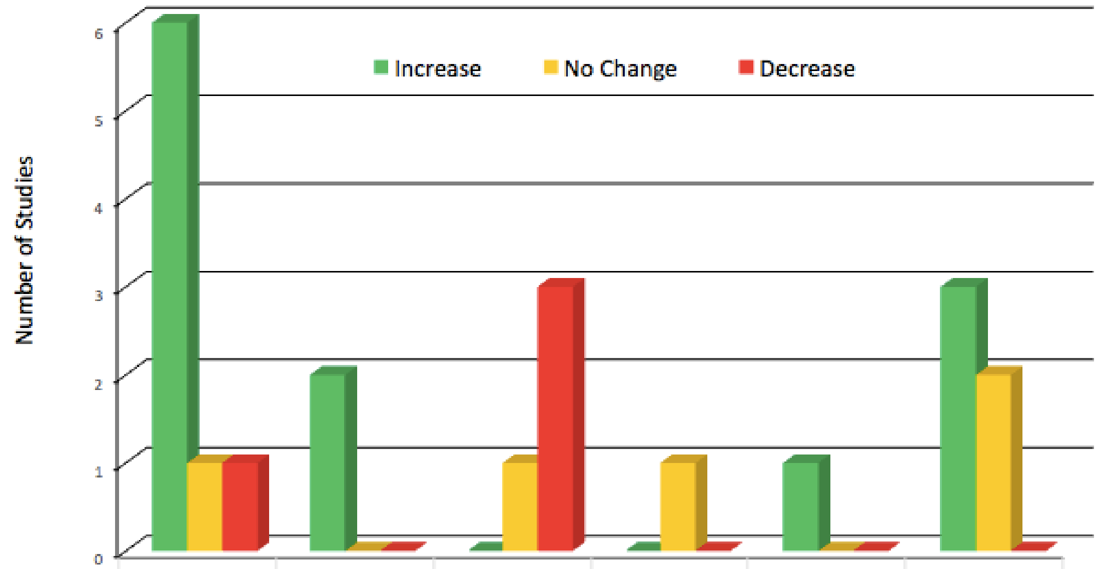
Definition: Hedges or hedgerows are lines of vegetation such as shrubs and trees of 1 to 5 m wide that form field boundaries and are generally managed by cutting and/or laying and coppicing. They are associated with a number of ecosystem benefits, such as providing various animals with a corridor to move through and enhancing pollination by slowing down air fluxes and trapping air-borne pollen grains.

Key Messages

- In contrast to our understanding of above-ground hedgerow function, little is known about how hedgerow field margins affect the below-ground soil system.
- Soil under hedges stores more carbon than adjacent arable soil.

Review Findings

Compared to arable soil, soil under hedges had significantly higher soil organic carbon (SOC) storage, aggregate stability, hydraulic conductivity and earthworms (Figure 4.5). Soils under hedges also had a significantly lower bulk density than arable soils. However, the strength of the evidence available for soil organic carbon storage in this review was judged to be moderate because about half of the studies did not have a well-defined experimental control. In addition, there were only 12 studies. See Appendix 7 for further information.



	SOC Stocks	Aggregate Stability	* Bulk density	Infiltration	Hydraulic Conductivity	Earthworms
Increase	6	2	0	0	1	3
No Change	1	0	1	1	0	2
Decrease	1	0	3	0	0	0

* Decreases in these indicators improve soil health

Strength of Evidence: Strong

Figure 4.5: Summary of Findings for Hedges (n=12 studies)

Strength of evidence

Moderate: About half of the data were from field experiments with no clearly defined control and some of the data came from modelling studies.

Gaps in knowledge

- Very few studies have investigated the impact of hedges on soil infiltration and hydraulic conductivity, which have implications for water retention or loss.
- Most studies have only compared soils under hedges with the soils in arable fields. There is a need to compare arable fields with and without hedges to determine what effects hedges may have on the soils of arable fields, especially downslope from hedges, which may affect hydrological functions.
- Only one study compared soil health indicators under hedges with those in grassland soils.
- No studies reported the impact on soil health of planting new hedges on agricultural land, and information is required on the timescales over which such new hedges affect soil.

4.2.6 Grass leys in arable systems

Definition: Short-term agricultural grassland, usually sown as part of an arable rotation, to provide hay, silage and grazing for a few years (normally less than five). Most short-term leys will consist of perennial ryegrass and white or red clover. The inclusion of grass and/or legume leys in arable rotations can be used to manage weed problems, such as black-grass, and/or to build soil fertility. Recently developed herbal leys with deeper rooting mixtures of grasses, legumes and forbs, which are being used in the UK, have not yet been evaluated for their effects on soil health in the academic literature.

Messages

- Using grass and grass-clover leys in arable rotation increases soil organic carbon stock and the number of earthworms.

Review Findings

The results in Figure 4.6 show that introducing grass and grass-clover leys into arable rotation resulted in a significant increase in soil organic carbon (SOC) storage and earthworm population. However, only one study reported on the impact of leys on earthworms. A greater number of studies reported an increase in SOC storage when grass leys were included in arable rotation compared to the inclusion of grass-clover leys (see Appendix 8). This is perhaps because plant species differ in their level of biomass production (Wilsey, 2007) and turnover. Perennial ryegrass (*Lolium perenne* L) was predominantly used in grass leys, whereas clover (*Trifolium repens* L. or *Trofolium pratense* L.) was the main legume used in leys. Rasmussen et al. (2010) showed that clover has a higher turnover of below ground biomass and carbon loss than perennial rye grass. This might be the reason for the higher SOC in grass leys than in grass-legume leys. However, including legumes has the added benefit of improving soil nutrients, particularly nitrogen.

Introducing grass and clover leys into arable rotation also resulted in a significant increase in soil aggregate stability, and a significant decrease in bulk density. However, these effects were based on a very small number of studies, hence more studies are needed. See Appendix 8 for further information.

	SOC Stock	Aggregate Stability	* Bulk density	Water Holding Capacity	Earthworms
Increase	14	1	0	0	3
No Change	4	0	1	1	0
Decrease	0	0	1	0	0

* Decreases in these indicators improve soil health

Strength of Evidence: Strong

Figure 4.6: Summary of Findings for Grass leys in arable systems (n=15 studies)

Strength of evidence

Strong: Data were based on results of field experiments.

Gaps in knowledge

- There is limited research on the effects of introducing grass leys into arable rotation on soil aggregate stability, bulk density and infiltration.
- There are no published papers in the academic literature on how herbal leys with deeper rooting mixtures of grasses, legumes and forbs impact on soil health.

4.2.7 Addition of organic amendments

Definition: Organic amendments are materials of plant or animal origin, such as animal manure and crop residues, that are added to the soil in order to improve its physical properties, including water retention, permeability, water infiltration, drainage, aeration and structure, by increasing the soil's organic matter content. In addition, this should lead to an increase in soil fertility and a decline in the use of inorganic fertilisers.

Key Messages

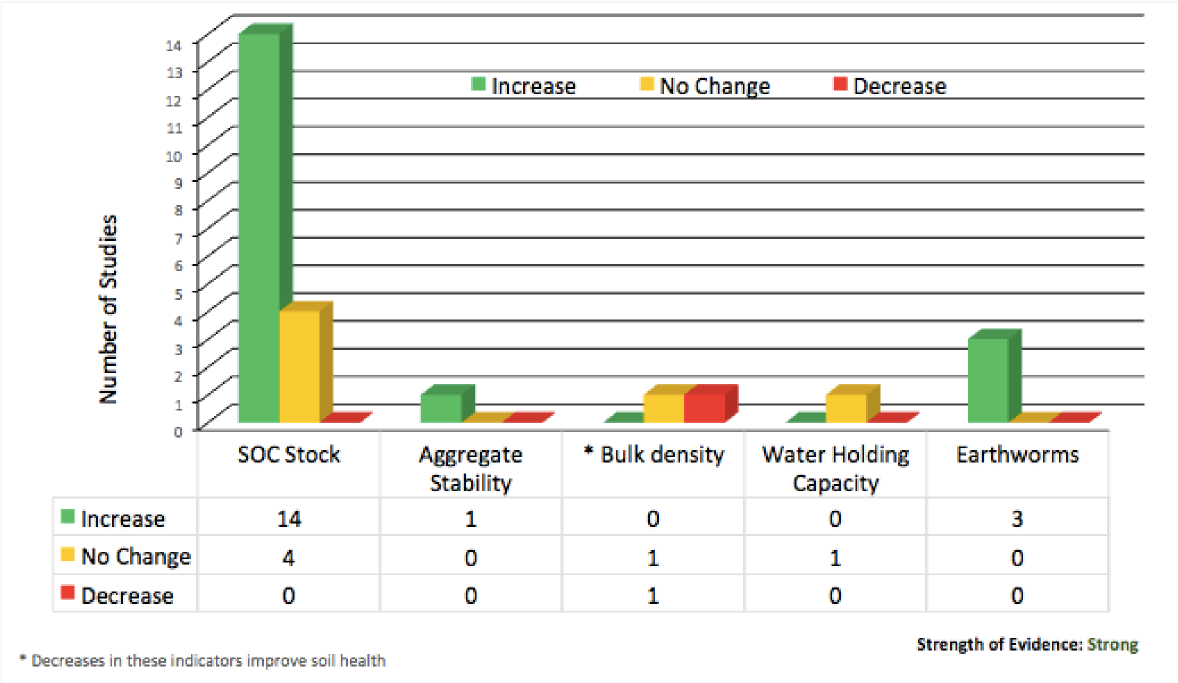
- Organic amendments increase soil organic carbon stock, aggregate stability and earthworm population.
- Evidence for the positive effects of compost and sewage sludge on soil health is limited.

Review Findings

Organic amendments lead to a significant increase in soil organic carbon (SOC) storage, aggregate stability and earthworm population (Figure 4.7). The percentage of the total number of studies that reported these positive effects on the soil health indicators was 83% for aggregate stability, 70% for earthworm population and 69% for SOC storage. These positive effects were observed across various types of organic amendments including the retention of crop residues in the field and the addition of farmyard manure.

Soil health parameters were also improved by the addition of compost and sewage sludge. However, the evidence for the effects of compost and sewage sludge on soil health was based on only one or two studies.

The results of this review strongly suggest that organic amendment is an effective strategy for improving soil health. By enhancing SOC storage, aggregate stability and earthworm population, this intervention is highly likely also to improve nutrient and water retention in the soil, thereby increasing crop productivity. However, some of the amendments, such as sewage sludge and animal slurry, could lead to the build-up of pollutants such as phosphorus and pharmaceuticals which could end up in water courses and plants. See Appendix 9 for further information.



	SOC Stock	Aggregate Stability	* Bulk density	Water Holding Capacity	Earthworms
Increase	14	1	0	0	3
No Change	4	0	1	1	0
Decrease	0	0	1	0	0

Table 4.7: Summary of Findings for Addition of organic amendments (n=26 studies)

Strength of evidence

Strong: Data were based on results of field experiments.

Gaps in knowledge

- Very few studies have investigated the effects of compost, sewage sludge and biosolids on soil health indicators.
- The potential effects of some organic amendments such as sewage sludge on soil-plant system and environmental pollution need to be investigated.

4.2.8 Leaving stubble overwinter

Definition: Overwinter stubble is the practice of leaving the stalks of cereal crops in the field after harvest (it does not include maize). The practice has been shown to attract large numbers of bird species of conservation concern. It also helps to control weeds and soil erosion by ensuring the ground is covered over-winter.

Key Messages

- Stubble retention in arable fields has no significant effects on soil organic carbon storage and earthworm population, but the evidence for this is based on a limited number of studies.

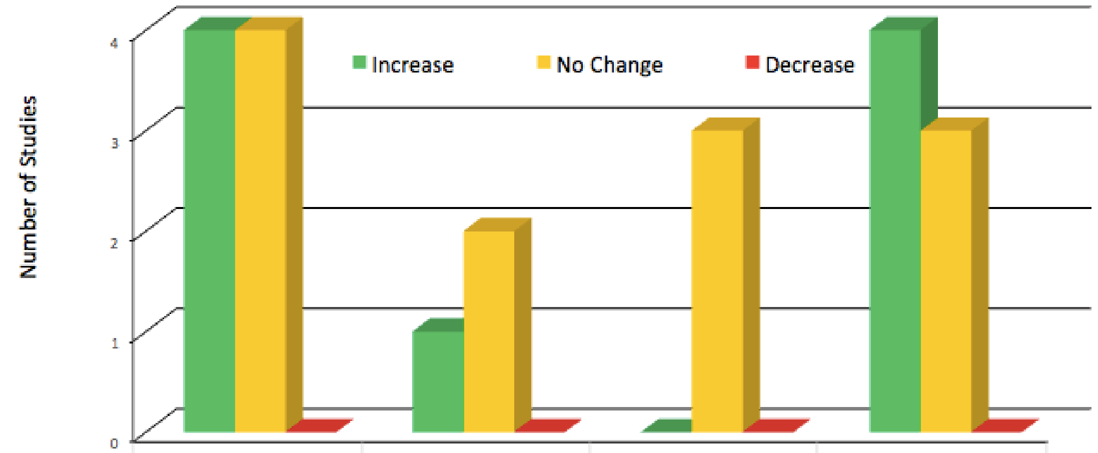
Review Findings

Figure 4.8 combines the results of the ten studies reviewed. Half of the eight studies that reported changes in SOC and four of the seven studies that reported changes in earthworm numbers found that stubble retention resulted in an increase in SOC storage and earthworm population, respectively. The remaining studies showed that stubble retention had no significant effects on these soil health parameters. It is, however, important to note that only three studies out of the ten reviewed were from Europe and North America. These three studies were the only ones that compared the effects of stubble retention against stubble removal. Results from these three studies showed that there was no significant difference in soil organic carbon (SOC) storage, bulk density and earthworm population between the soils of the fields with and without stubbles.

The seven studies outside Europe and North America compared the effects of stubble retention with those of stubble burning, which is banned in the UK. Results from these studies showed that fields where stubbles were retained had significantly higher SOC storage and earthworm population. The apparent positive effect of stubble retention here might just be a reflection of the negative effects of burning. Thus, the results of these seven studies do not provide sufficient evidence for the effects of stubble retention in arable fields on soil health.

With the limited number of studies directly investigating the effects on soil health of leaving stubble to overwinter, it is difficult to reach a conclusion on its impact on soil health.

However, stubble provides a good soil surface cover, which is important for soil erosion control. See Appendix 10 for further information.



	SOC Stock	Aggregate Stability	* Bulk density	Earthworms
Increase	4	1	0	4
No Change	4	2	3	3
Decrease	0	0	0	0

* Decreases in these indicators improve soil health

Strength of Evidence: Strong

Figure 4.8: Summary of Findings for Leaving stubble overwinter (n=10 studies)

Strength of evidence

Strong: Data were based on results of field experiments.

Gaps in knowledge

- Very few studies compared the soil health of arable fields with and without stubble retention and none were from Europe.

4.2.9 Tillage practice

Definition: Tillage is the term for preparing soil, e.g. breaking up large clods, so that it is ready for sowing new crops. Tillage practices vary but can be broadly grouped into two: conventional tillage and conservation tillage. Under conventional tillage, the soil is ploughed and inverted to a depth of at least 20 cm, followed by harrowing, disking or tining to create a seedbed. Conservation tillage, also known as reduced tillage or minimum tillage, refers to a non-plough based tillage, usually with shallow disking that leaves at least 30% of the soil surface covered by crop remains. Zero tillage or no tillage is an extreme form of conservation tillage where seed is drilled directly into uncultivated soil.

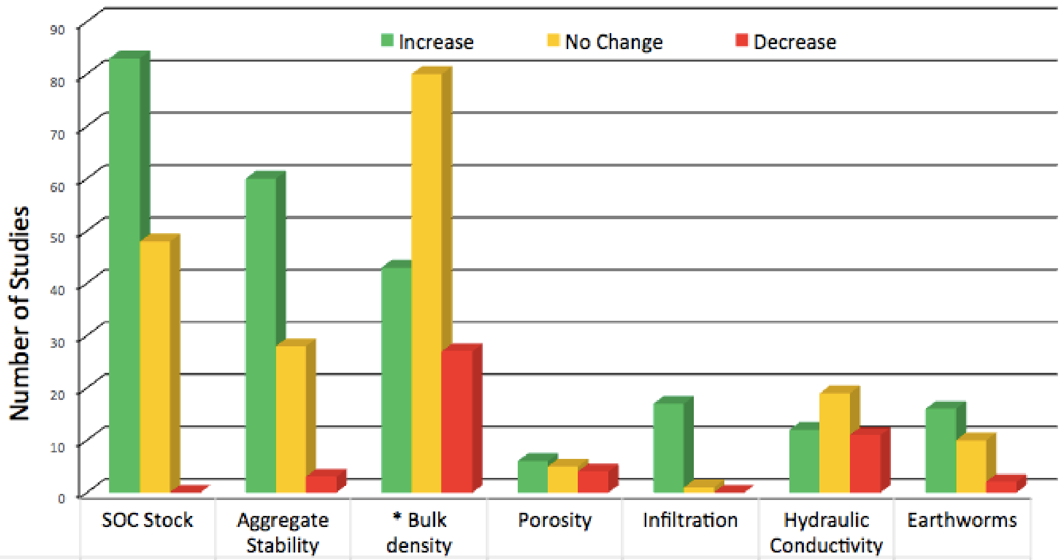
Key Messages

- Conservation tillage can significantly improve soil health compared to conventional tillage.
- The effects of conservation tillage on some soil health parameters such as bulk density and hydraulic conductivity can vary depending on the type of conservation tillage and site characteristics (see Appendix 11 for more detail).

Review Findings

The balance of evidence in this review is that conservation tillage improves key soil health parameters such as SOC storage, aggregate stability, total porosity, infiltration and earthworm population. This review therefore strongly suggests that reducing the intensity of tillage has the potential to improve soil health significantly. However, weed control can be an issue in no-tillage systems, resulting in increased used of herbicides on crops. In organic systems, a weed control system other than ploughing must be developed if no-till cultivation is to be used.

Figure 4.9 summarises the effects of conservation tillage on soil organic carbon (SOC) storage, aggregate stability, bulk density, total porosity, infiltration, hydraulic conductivity and earthworm population. The responses of these soil health parameters to conservation tillage varied, with significant increase, significant decrease and no change reported (see Appendix 11). However, based on the frequency of effects reported in the academic literature (Figure 4.9), conservation tillage (when compared with conventional tillage) led to a significant increase in SOC storage, aggregate stability, total porosity, infiltration and earthworm population. More than half of the reviewed studies found no significant difference in soil bulk density between fields under conventional and fields under conservation tillage, whereas in 29% of the studies, fields under conservation tillage had significantly higher soil bulk density than the fields under conventional tillage. The variability in the effects of conservation tillage on bulk density could be attributed to the differences in specific management activities that constitute conservation tillage. For example, in some conservation tillage practices such as direct drilling, there is minimal soil disturbance and the bulk density tends to be higher than in conventional tillage. In contrast, harrowing, which is often considered a type of conservation tillage, tends to loosen the soil thereby creating a similar effect (i.e. reduction) on bulk density as conventional tillage. Similarly to the reported results on bulk density, the reported response of hydraulic conductivity to conservation tillage was also variable, and this could be attributed to the differences in the level of soil disturbance/loosening. See Appendix 11 for further information.



	SOC Stock	Aggregate Stability	* Bulk density	Porosity	Infiltration	Hydraulic Conductivity	Earthworms
Increase	83	60	43	6	17	12	16
No Change	48	28	80	5	1	19	10
Decrease	0	3	27	4	0	11	2

* Decreases in these indicators improve soil health

Strength of Evidence: Strong

Figure 4.9: Summary of Findings for Tillage practice (n=90 studies)

Strength of evidence

Strong: Data were based on results of field experiments.

Gaps in knowledge

- Although this review suggests that conservation tillage improves soil health, it is not clear how the effects of the various practices within conservation tillage compare. For example, very few studies compared the effects of direct drilling on soil health indicators.

- 97% of studies only sampled the top 30 cm of the soil profile. Given the fact that those that have sampled soil at > 30 cm report that tillage practice influences the distribution of SOC but not the total SOC stock in the whole soil profile, it is important that more studies sample at depth. Without this information it is not possible to promote conservation tillage practices for climate change mitigation.

5. Summary and Concluding remarks

5.1 Synthesis of Results

The ten land management activities reviewed here can be split into: (i) land-use change (conversion of agricultural land to woodland) (ii) arable practices and (iii) linear features. The results from the review are summarised in Table 5 and the main findings synthesised below.

Land use change (LUC) – there is strong evidence that converting arable land to woodland can lead to an increase in soil organic carbon (SOC) storage and thus help to mitigate climate change. In contrast, there is strong evidence that afforestation of grasslands has no significant effect on SOC stock. Most studies investigated the impact of planting with coniferous species, so the impact of planting with native deciduous species on soil health indicators could not be evaluated. Very few studies reported on the impact of afforestation of agricultural land on hydrological indicators.

The conversion of arable land to woodland has a similar impact on soil health to many of the agricultural practices reviewed, thus there are various options for improving the health of arable soils that need to be considered together with goals of food production and delivery of multiple public goods.

Arable practice - soil health can be improved the most through (not in rank order) the following arable practices:

- Conservation tillage
- Introduction of grass and grass-clover leys into arable rotations
- Addition of organic amendments

All these options lead to an increase in SOC and may also build soil resilience given the important role that soil organic matter plays in soil functioning and improved crop yields. Whether these arable practices contribute to climate change mitigation depends on how SOC storage changes in the whole soil profile. Unfortunately, 97.5% of the studies reviewed only sampled the top 30 cm of the soil profile. All these agricultural practices also increased infiltration due to an improvement in soil structure and thus reduce surface runoff and help to mitigate flooding. Whether increased infiltration leads to an increase in leaching of nutrients is unclear; many studies show that leaching losses from conventional and conservation tillage are similar. The addition of some types of organic amendments may lead to water quality problems if the amendment is surface applied or contains high concentrations of nutrients, heavy metals, pathogens and emerging contaminants.

Cover crops and over-winter stubble (which can be considered a type of cover crop) do not lead to an improvement in our focal soil health indicators. However, they do not lead to deterioration in soil health either and so could be promoted without detriment to soil health on the basis of their role in reducing soil erosion and leaching of nutrients and thus help protect water quality. All of the studies reviewed the impact of single species on soil health indicators, but UK farmers are now using mixtures of species (e.g. mustards, radishes and grasses) in their cover crop; the ability of these mixtures to improve soil health and the delivery of public goods has yet to be evaluated.

Linear features - the database for evaluating the soil health impacts from the introduction of linear features into the farming environment is limited, particularly for hedges and agroforestry. More data are urgently needed given that hedges and buffer strips can have an impact on multiple public goods, and are both popular options in the current Countryside Stewardship Scheme. In addition, there is a lack of information about which species should be planted and how they should be managed for the delivery of soil-based environmental goods and services.

Soil depth - the review indicates that data are lacking on how soil health indicators and thus soil functions respond to changes in land management at depth (>30 cm), as most studies (93%) only sampled the top 30 cm. This is a major knowledge gap if we want to evaluate which agricultural practices can contribute to climate change mitigation, as some practices may result in a change in the SOC distribution but not the SOC stock in the whole profile (Sun et al., 2011).

Spatial scale of study - the vast majority of studies were carried out at field scale. Therefore it is important that we identify how public goods delivery at landscape scale can be measured, through e.g. large scale landscape networks, and/or modelling approaches.

Temporal scale of study – many of the studies were short-term (<5 years) with only 30 studies considering the impact of a particular land management activity on soil health for longer than 20 years. However, we know that many soil health indicators take time to respond to changes in land management, e.g. SOC, and the benefits of conservation tillage, agricultural conversion to woodlands and agroforestry may take many years to become apparent.

Yield and soil health - very few studies that reported the impact of land management activity on soil health indicators also measured the impact on crop yield. This makes it difficult to evaluate how best to develop agricultural systems that balance productivity with protecting and enhancing the environment.

Table 5. Matrix of land management versus soil health indicator. The effect of the intervention on soil health indicator were reported as either an increase, a decrease or no change (NC), the most frequently reported effect was considered to represent the overall effect. Only published papers with experimental control versus treatment and meta-analyses were included in the review. Green shading = overall positive effect, orange = no change and red = overall negative effect on soil health indicator (number of studies). Note a decrease in bulk density represents a positive impact, for all other soil indicators, an increase represents a positive impact.

	SOC stock	Bulk Density	Porosity	Hydraulic Conductivity	Infiltration	Aggregate Stability	Earthworm numbers	Water holding capacity
Agroforestry	Increase (4)	Decrease (2)	Increase (1)	Increase (2)			Increase (1)	
Buffer Strip	Increase(15) NC (6) Decrease(3)	Decrease (11) NC (1) Increase (1)	Increase (2)	Increase (2) NC (2)	Increase (4) NC (3)	Increase (5)	Increase (7) NC (9) Decrease (2)	Increase (1)
Cover Crops	NC (24) Decrease (1)	Decrease (2) NC (20) Increase (1)	Increase (5) NC (6)	NC (1) Decrease (4)		Increase (7) NC (10) Decrease (2)		
Arable to Woodland	Increase (4) NC (2) Decrease (2)	Decrease (2) NC (2)	Increase (2)	Increase (2)				
Grass to Woodland	Increase (2) NC (11) Decrease (9)	Decrease (3) NC (11) Increase (2)		Increase (1)	Increase (1)	NC (1)		
Hedges	Increase (6) NC (1) Decrease (1)	Decrease (3) NC (1)		Increase (1)	NC (1)	Increase (2)	Increase (3) NC (2)	
Leys in arable rotations	Increase (14) NC (4)	Decrease (1) NC (1)				Increase (1)	Increase (3)	NC (1)
Organic Amendments	Increase (20) NC (9)	NC (2)				Increase (10) NC (2)	Increase (7) NC (2) Decrease (1)	
Crop Stubble over Winter	Increase (4) NC (4)	NC (3)				Increase (1) NC (2)	Increase (4) NC (3)	
Conservation Tillage	Increase (83) NC (48)	Decrease (27) NC (80) Increase (43)	Increase (6) NC (5) Decrease (4)	Increase (12) NC (19) Decrease (11)	Increase (17) NC (1)	Increase (60) NC (28) Decrease (3)	Increase (16) NC (10) Decrease (2)	

5.2 Trade-offs between public goods

In this study we only reviewed the evidence that exists for the impact of ten land management activities on eight key soil health indicators. We did not review their impact on a wider range of environmental, economic and health effects such as diffuse pollution, biodiversity, and human health. This type of review would have taken considerably longer to carry out and was out of scope. However, it is worth considering that there are very few studies that have drawn together information on the potential of different land management activities/interventions to deliver multiply public goods, given the intention of the new ELMS. Those that have, all highlight that no single land use/mitigation option will lead to an improvement in all public goods. For example, Stevens and Quinton (2009) reviewed the impact of six common diffuse pollution mitigation options in arable systems and highlighted that no single mitigation option will reduce all pollutants and that '**pollution swapping'** can occur. An example of a best management practice where pollution swapping is known to occur is the riparian buffer strip. The buffer strip is introduced to reduce nitrate leaching from soil to surface water, and thus improve water quality, but in doing so inadvertently leads to an increase in another pollutant, nitrous oxide, which is produced when nitrate is removed by denitrification and emitted to the atmosphere where it can contribute to global warming and air pollution. Thus while buffer strips can lead to an improvement in some public goods, such as water quality and climate change mitigation, they can lead to a deterioration in other public goods, such as air quality. Other land management activities can also help to improve some public goods but lead to a deterioration in others. For example, Holden et al. (2018) showed that while hedges could be of benefit for reducing flood risk and enhancing total soil carbon storage, their impact on water quality may be negative because of the capture of air pollutants by the hedge.

A recent study by McKay et al., (2019) investigated the degree to which sustainable intensification (SI), whereby food production increases while environmental impacts are reduced, has occurred in the South West (livestock) and Eastern (arable) regions of England. They found that while most ecosystem services, except farmland biodiversity, had started to recover post 2000, the reduction in UK food self-sufficiency resulting in some agricultural impacts being 'offshored', represent major negative trade-offs. Thus there is a need to quantify the trade-off between improvement in some public goods and deterioration in others. When considering which land management intervention to use, a major consideration should be which public good(s) is the target of concern. Some may have a higher priority than others, so specific land management activities might then be adopted to tackle those, even at the expense of those with a lower priority. In addition, a land management activity should be selected that is appropriate to the farm type (arable, livestock, mixed) and location, including soil type, hydrological setting, climate, and location in the catchment.

5.3 Application of Systematic Review methods

In this study we applied a systematic review methodology. However, by applying such a methodology we came across a number of issues in collating data that meant the review has used the vote account method to assess the numbers of statements reporting a particular influence on each soil health indicator. This method was in preference to a quantitative meta-analysis which gives the effect size and percentage change in a soil health indicator as a result of implementing an agricultural intervention in comparison to a control.

The challenges in synthesising information in environmental science systematic reviews are linked to:

1. The heterogeneous nature of the agricultural practice in terms of site, soil type, climate, crop species and management practices (tillage, fertiliser, manure/slurry etc.)
2. Methodological discrepancies related to, among others, soil sampling depth, sample preparation, experimental design, and calculation and presentation of results.

These factors lead to a wide range of different observations being recorded and, in meta-analyses, wide confidence intervals (e.g. see De Stefano & Jacobson, 2018). However, if only the studies that included information on measures of variation and sample size, which are needed for meta-analysis, were included, the available database would have been further constrained and in this study the database for some agricultural practices was already small.

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5.4 Conclusions and recommendations

- Our approach has focussed on a set of soil health indicators that are important for soil functions and the delivery of public goods and services, but is not exhaustive, and has not included components such as biodiversity and soil microbiology which are complex to interpret, but may also be important.
- We have highlighted, from a list of ten, which land management interventions lead to an improvement in some key indicators of **soil health** and the delivery of other public goods, such as climate change mitigation, improved water quality and flood alleviation.

- The gaps in evidence that the report highlights can provide a focus for future and current research, including Defra-funded trials, use of transition period funding, UKRI-NERC/BBSRC programmes and consortia of public and private funders.
- It is critical that this research is done with a range of stakeholders, including land managers and academics, to enable immediate use in informing the new ELMS.
- There is a need for critical assessment of the ability of different interventions to **deliver multiple public goods**. This information is currently lacking in academic literature and is urgently needed. The same mitigation option will not result in the same impact everywhere due to variations in soil type, climate, crop rotation, fertilizer application and land management practices. Sometimes, although we may see an improvement in one targeted public good, e.g. soil health, it may result in the deterioration of another public good.
- We need to be realistic about time frames as many soil health indicators take time to respond to changes in land management. For example, the benefits of conservation tillage or land-use change to woodlands and agroforestry may take many years (20-50 years) to become apparent.

Policy options:

- Given the lack of data on how different interventions impact upon soil health and the delivery of multiple public goods, it may be best to build flexibility into the ELMS so that activities can be reviewed/added/removed as evidence becomes available.
- Codes of good practice could be made part of ELMS, similarly to the recent Defra Code of Good Agricultural Practice for Reducing Ammonia Emissions, which provides simple, evidence-based ways to reduce ammonia emissions.

6. References

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Appendix 1: Definitions

Aggregate stability refers to the ability of soil aggregates (groups of soil particles that bind to each other more strongly than to adjacent particles) to resist disintegration when disruptive forces associated with water, wind or tillage are applied. **Water stable aggregates** gives an indication of how well a soil can resist raindrop impact and water erosion. It is also an indicator of a soil's resistance to compaction. Aggregate stability is critical for infiltration, root growth and resistance to water and wind erosion. Unstable aggregates easily disintegrate during rainstorms and the dispersed soil particles fill surface pores and a hard physical crust can develop when the soil dries. Soil crusts lead to a reduced infiltration, which can result in increased runoff and water erosion, and reduced water available in the soil for plant growth. Aggregate stability can be improved by land management practices that increase soil organic matter content.

Bulk Density is the weight of dry soil per unit volume of soil and is normally expressed in grams/cm^3. Bulk density considers both the solids and the pore space. It is dependent on soil texture, soil structure and soil organic matter and **its value increases with compaction**. It also affects other soil properties such as porosity, infiltration, rooting depth, available water capacity, plant nutrient availability, and soil microorganism activity, which influence key soil functions and productivity. Bulk density is therefore used as an indicator of soil compaction and soil health. Bulk density can be changed by land management practices that affect soil cover, organic matter content, soil structure, compaction and porosity.

Earthworms are burrowing annelid worms that live in the soil and perform several important functions. They improve soil structure, water movement, nutrient cycling and plant growth. For example, earthworms can increase pore space and create continuous pores linking surface soil layers to subsurface soil layers and thus influence infiltration. As their presence is usually an indicator of a healthy system, the numbers of earthworms in a field are often used as an indicator of soil health.

Hydraulic conductivity (*K*) describes the ease with which pores of a saturated soil permit water movement. It is a quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient and it is affected by soil texture and structure as it depends on the soil pore geometry and connectivity.

Infiltration refers to the soil's ability to allow water movement into and through the soil. Infiltration rates are a measure of how fast water enters the soil and are typically expressed in mm/hour. It allows the soil to temporarily store water, making it available for root uptake, plant growth and habitat for soil organisms. The infiltration capacity is the maximum rate that water can move into the soil surface and it varies over time (seasonally and during an individual rainfall event). When rainfall, irrigation or snowmelt occurs at a rate that exceeds the soil's infiltration capacity, water ponds on the surface and can flow downslope as runoff once the ponded regions start to overflow. Ponding results in poor soil aeration, which leads to poor root function, poor plant growth and reduced cycling of nutrients by soil organisms. When runoff occurs on bare or poorly vegetated soil, erosion usually occurs. Erosion leads to the transport of soil, nutrients and chemicals from the land to water bodies, resulting in decreased soil productivity, sedimentation of water bodies, and deterioration in water quality. Land management practices that increase vegetation cover and soil organic matter content can help maintain or improve infiltration. Such practices include those that minimise soil disturbance and compaction, protect from soil erosion and encourage development of a good soil structure.

Porosity or **pore space** refers to the volume of soil voids that can be filled by water and/or air. It is inversely related to bulk density. Porosity is calculated as a percentage of the soil volume. Compaction decreases porosity as bulk density increases. For example, if compaction increases bulk density from 1.3 to 1.5 g/cm^3, porosity decreases from 50 percent to 43 percent. Porosity, however, does not tell us anything about the size of pores or their connectivity.

Soil organic carbon (SOC) refers only to the carbon content of organic compounds in soil organic matter (SOM). About 58% of the mass of soil organic matter exists as carbon. Soil organic carbon stock in tonnes of carbon per hectare (t C ha^{-1}) = total organic carbon (%) x mass of soil in a given volume (bulk density). Changes in SOC generally occur very slowly (over decades) and it is often hard to measure small changes against a relatively large background of soil carbon. The SOC stock is increased by land management practices that increase soil organic matter content.

Soil organic matter (SOM) is the fraction of the soil that consists of plant or animal tissue in various stages of breakdown (decomposition). Organic matter makes up just 2–10% of the soils mass but has a critical role in the physical, chemical and biological function of soils. Soil organic matter binds soil particles together in **stable aggregates** and promotes good soil structure; increasing porosity and infiltration. Soils with a high content of organic matter also provide good habitat for soil biota, such as earthworms.

Soil Structure is defined by the way individual soil particles (sand, clay, silt and organic matter) are assembled into units called soil **aggregates**. Aggregation of soil particles can occur in different shapes (granules, crumbs or blocks) resulting in different soil structures. A good soil structure is important to allow air and water into the soil which are vital for healthy plant growth. It also helps drainage and reduces soil erosion caused by excess surface run-off. A poor soil structure results in a decline in infiltration, increase in bulk density and poor plant growth. Increasing soil organic matter content helps create and stabilise soil structure.

Soil Texture refers to the proportion by weight of different sized particles (sand, silt and clay) in the soil and **cannot be altered by land management**. It is a key soil property as it controls the water holding capacity of a soil and influences infiltration and hydraulic conductivity.

Water Holding Capacity is the total amount of water a soil can hold at field capacity. **Field Capacity** is the amount of soil moisture or water content held in the soil after excess water has drained away and the rate of downward movement has decreased. This usually takes place 2–3 days after rain or irrigation. Soil texture and organic matter are the key components that determine soil water holding capacity. The larger the soil surface area the easier it is for the soil to hold onto water so clay rich soils have higher water holding capacities than sandy soils. Water holding capacity increases with increasing soil organic matter content.

Appendix 2: Search terms.

The * character was a wildcard used in the database search to pick up all variations of a root word.

Intervention terms	Soil health terms
Cover crop: cover crops, cover cropping, spring cover crop, winter cover crop	soil organic matter, soil organic carbon, SOC stock, SOC storage, loss on ignition, soil structure, soil bulk density, soil porosity, infiltration, earthworm, water stable aggregates, aggregate stability, hydraulic conductivity, soil texture, permeability, water holding capacity
Introducing leys: ley, grass ley, grass in rotation, legumes in rotation, legume ley	
Organic amendment: crop residue, return of crop residue, organic amendment	
Overwinter stubble: overwinter stubble, stubble mulch, stubble cover, stubble	
Tillage: no till, minimum till, conservation tillage, zero tillage, direct drill	
Arable/grassland to woodland: land use change, land use conversion, land use transition, land cover change, land cover conversion, land cover transition, land management change, land management conversion, land management transition, agri-environmental management, land allocation, arable conversion, land abandonment, abandonment, succession, afforest*, reforest*, wood*, tree*, forest	
Linear features (hedges, buffer strips, beetle banks and agroforestry): agroforestry, silvoarable, silvopastoral, agrosilvopastoral, farm woodland*, forest farming*, forest grazing, grazed forest*, isolated trees, scattered tree, tree outside forest*, farm tree*, woodlot*, timber tree system, dehesa, montado*, oak tree*, olive tree*, fruit tree*, pré-verger, Streuobst, pomarada*, Hauberg, Joualle, orchard system, orchard intercropping, parkland*, alley cropping, wooded pasture*, wood pasture*, pollarding, fodder tree*, pannage, *grass barrier*, grassed barrier*, grassy barrier*, managed barrier*, riparian barrier*, sown barrier*, uncropped barrier*, un-cropped barrier*, unmanaged barrier*, unploughed barrier*, un-ploughed barrier*, vegetated barrier*, vegetation barrier*, vegetative barrier*, forest barrier*, forested barrier*, noncropped barrier*, non-cropped barrier*, plant barrier*, planted barrier*, *flower barrier*, wood barrier*, wooded barrier*, woody barrier*, herbacious barrier*, cultivated barrier*, uncultivated barrier*, bird cover barrier*, grazed barrier*, weedy barrier*, weeded barrier*, perennial barrier*, *grass border*, grassed border*, grassy border*, managed border*, riparian border*, sown border*, uncropped border*, un-cropped border*, unmanaged border*, "unploughed border*, un-ploughed border*, vegetated border*, vegetation border*, vegetative border*, forest border*, forested border*, noncropped border*, non-cropped border*, plant border*, planted border*, *flower border*, wood border*, wooded border*, woody border*, herbacious border*, cultivated border*, uncultivated border*, bird cover border*, grazed border*, weedy border*, weeded	

border*, perennial border*, *grass boundar*, grassed boundar*, grassy boundar*, managed boundar*, riparian boundar*, sown boundar*, uncropped boundar*, un-cropped boundar*, unmanaged boundar*, unploughed boundar*, un-ploughed boundar*, vegetated boundar*, vegetation boundar*, vegetative boundar*, forest boundar*, forested boundar*, noncropped boundar*, non-cropped boundar*, plant boundar*, planted boundar*, *flower boundar*, wood boundar*, wooded boundar*, woody boundar*, herbacious boundar*, cultivated boundar*, uncultivated boundar*, bird cover boundar*, grazed boundar*, weedy boundar*, weeded boundar*, perennial boundar*, *grass buffer*, grassed buffer*, grassy buffer*, managed buffer*, riparian buffer*, sown buffer*, uncropped buffer*, un-cropped buffer*, unmanaged buffer*, unploughed buffer*, un-ploughed buffer*, vegetated buffer*, vegetation buffer*, vegetative buffer*, forest buffer*, forested buffer*, noncropped buffer*, non-cropped buffer*, plant buffer*, planted buffer*, *flower buffer*, wood buffer*, wooded buffer*, woody buffer*, herbacious buffer*, cultivated buffer*, uncultivated buffer*, bird cover buffer*, grazed buffer*, weedy buffer*, weeded buffer*, perennial buffer*, *grass filter*, grassed filter*, grassy filter*, managed filter*, riparian filter*, sown filter*, uncropped filter*, un-cropped filter*, unmanaged filter*, unploughed filter*, un-ploughed filter*, vegetated filter*, vegetation filter*, vegetative filter*, forest filter*, forested filter*, noncropped filter*, non-cropped filter*, plant filter*, planted filter*, *flower filter*, wood filter*, wooded filter*, woody filter*, herbacious filter*, cultivated filter*, uncultivated filter*, bird cover filter*, grazed filter*, weedy filter*, weeded filter*, perennial filter*, *grass margin*, grassed margin*, grassy margin*, managed margin*, riparian margin*, sown margin*, uncropped margin*, un-cropped margin*, unmanaged margin*, unploughed margin*, un-ploughed margin*, vegetated margin*, vegetation margin*, vegetative margin*, forest margin*, forested margin*, noncropped margin*, non-cropped margin*, plant margin*, planted margin*, *flower margin*, wood margin*, wooded margin*, woody margin*, herbacious margin*, cultivated margin*, uncultivated margin*, bird cover margin*, grazed margin*, weedy margin*, weeded margin*, perennial margin*, *grass strip*, grassed strip*, grassy strip*, managed strip*, riparian strip*, sown strip*, uncropped strip*, un-cropped strip*, unmanaged strip*, unploughed strip*, un-ploughed strip*, vegetated strip*, vegetation strip*, vegetative strip*, forest strip*, forested strip*, noncropped strip*, non-cropped strip*, plant strip*, planted strip*, *flower strip*, wood strip*, wooded strip*, woody strip*, herbacious strip*, cultivated strip*, uncultivated strip*, bird cover strip*, grazed strip*, weedy strip*, weeded strip*, perennial strip*, *grass zone*, grassed zone*, grassy zone*, managed zone*, riparian zone*, sown zone*, uncropped zone*, un-cropped zone*, unmanaged zone*, unploughed zone*, un-ploughed zone*, vegetated zone*, vegetation zone*, vegetative zone*, forest zone*, forested zone*, noncropped zone*, non-cropped zone*, plant zone*, planted zone*, *flower zone*, wood zone*,	

wooded zone*, woody zone*, herbacious zone*, cultivated zone*, uncultivated zone*, bird cover zone*, grazed zone*, weedy zone*, weeded zone*, perennial zone*, barrier strip*, border strip*, boundary buffer*, boundary margin*, boundary strip*, boundary management*, field border*, field buffer*, field margin*, buffer strip*, buffer zone*, filter strip*, filter zone*, managed edge*, buffer management*, bufferstrip*, bufferzone*, cropland buffer*, farmland buffer*, farmland margin*, ditch bank*, farm buffer*, farm edge*, farm interface*, field bank*, field boundary*, field edge*, field interface*, filter margin*, filter strip*, filterstrip*, filter zone*, filterzone*, margin strip*, beetlebank*, beetle bank*, hedge row*, hedgerow*, shelterbelt*, shelter belt*, grassed waterway*, grassed water way*, grass waterway*, grass water way*, grassy waterway*, grassy water way*, vegetated waterway*, vegetated water way*, vegetative waterway*, vegetative water way*, wind buffer*, agroforestry buffer*, conservation buffer*, conservation headland*, conservation head land*, stream border*, stream barrier*, stream buffer*, stream margin*, river border*, river barrier*, river buffer*, river margin*, waterway border*, waterway buffer*, waterway margin*, water way border*, water way buffer*, water way maring*, countour strip*, nectar strip*, widlife strip*, wildlife corridor*, set-aside margin*, set-aside border*, set-aside buffer*, setaside margin*, setaside border*, setaside buffer*, permanent strip*, permanent margin*, permanent border* permanent buffer*, sterile strip*).	

Appendix 3: Data on Agroforestry

Table 3.1: Overall effects of agroforestry on soil health parameters (n=7 studies).

Soil health parameter	**Response of soil heath parameters to agroforestry (number of datasets)**				**Strength of evidence**
	Significant increase	**No significant change**	**Significant decrease**	**Mixed responses**	
Soil organic carbon storage	4	0	0	0	Strong (All data, except conclusions from two narrative review papers, were based on results of field experiments)
Bulk density	0	0	2	0	
Total porosity	1	0	0	0	
Hydraulic conductivity	2	0	0	0	
Earthworm population	1	0	0	0	

Table 3.2: Impacts of agroforestry on soil health (SOC = soil organic carbon). Number of studies = 7.

Intervention	**Soil health parameter**	**Effect of intervention (number of datasets)**	**Quality of evidence**	**Source of evidence (country and number of studies)**
Agroforestry	SOC storage	Significant increase (4); No significant effect (0); Significance reduction (0)	Strong (All data, except conclusions from two narrative review papers, were based on results of field experiments)	Canada (1), USA (2), Worldwide (4)
	Bulk density	Significant increase (0); No significant effect (0); Significance reduction (2)		
	Hydraulic conductivity	Significant increase (2); No significant effect (0); Significance reduction (0)		
	Total porosity	Significant increase (1); No significant effect (0); Significance reduction (0)		
	Earthworm population	Significant increase (1); No significant effect (0); Significance reduction (0)		

Table 3.3: Study location (n=7)

Country	**n**
Canada	1
USA	2
Combination of different countries	4

Table 3.4: Summary of study type, scale and duration (n=7)

Study type	**n**
BACI	1
Control vs. treatment	6
Scale	
Field	1
Farm	1
Watershed	1
Not specified	4
Duration	
<10	2
10 - 20	2
Combination different duration categories (e.g. 10-20 and 20-30)	1
Not specified	2

Appendix 4: Data on Buffer strips

Table 4.1: Overall effects of agroforestry on soil health parameters (n=23).

Soil health parameter	**Response of soil heath parameters to buffer strips (number of datasets)**				**Strength of evidence**
	Significant increase	**No significant change**	**Significant decrease**	**Mixed responses**	
Soil organic carbon storage	8	5	3	0	Strong (All data were collected from field experiments excluding one modelling study and one review)
Aggregate stability	5	0	0	0	
Bulk density	1	1	8	0	
Total porosity	1	0	0	0	
Water holding capacity	1	0	0	0	
Hydraulic conductivity	1	1	0	0	
Infiltration	5	4	0	0	
Earthworm population	6	7	1	0	

Table 4.2: Impacts of buffer strips on soil health (SOC = soil organic carbon). Number of studies = 23.

Broad intervention	**Specific intervention**	**Soil health parameter**	**Effect of intervention (number of datasets)**	**Quality of evidence**	**Source of evidence (country and number of studies)**
Buffer strips	Grass buffer strips	SOC storage	Higher in buffer strips (8); no significant effect (3)	Strong (All data were collected from field experiments excluding one modelling study)	Canada (3), Italy (1), Netherlands (1), Sweden (1), USA (14), UK (1), Ireland (1), Review (1)
		Bulk density	Lower in buffer strips (5)		
		Hydraulic conductivity	Higher in buffer strips (1), no significant effect (1)		
		Earthworms	Higher in buffer strips (6), no significant effect (5), lower in buffer strips (2)		
		Porosity	Higher in buffer strips (1)		
		Water stable aggregates	Higher in buffer strips (3)		
		Infiltration	Higher in buffer strips (2), no significant effect (1),		
	Forested buffer strips	SOC storage	Higher in buffer strips (7); no significant effect (3); lower in buffer strips (3)	Strong (All data were collected from field experiments excluding one modelling study)	Canada (2), Italy (1), USA (11), Review (1)
		Bulk density	Higher in buffer strips (1), no significant effect (1); lower in buffer strips (6)		
		Earthworms	Higher in buffer strips (1), no significant effect (4)		

		Hydraulic conductivity	Higher in buffer strips (1), no significant effect (1)		
		Infiltration	Higher in buffer strips (2), No significant effect (2)		
		Porosity	Higher in buffer strips (1)		
		Water stable aggregates	Higher in buffer strips (2)		

Table 4.3: Study location (n=23)

Country	**n**
Canada	3
Italy	1
Netherlands	1
Sweden	1
USA	14
UK	1
Ireland	1
Combination of different countries	1

Table 4.4: Summary of study type and scale (n=23)

Study type	**n**
BACI	1
Control vs. treatment	18
Comparative	2
Modelling	1
Scale	
Plot	5
Field/site	6
Farm	1
Watershed	9

Table 4.5: Type of buffer strip (n=23)

Type of buffer strip	**n**
Grass	7
Forest	3
Grass and forest	11
Grass and agroforestry	1
Not reported	1

Appendix 5: Data on Cover Crops

Table 5.1: Overall effects of cover crops on soil health parameters (n=32).

Soil health parameter	**Response of soil heath parameters to cover crops (number of datasets)**				**Strength of evidence**
	Significant increase	**No significant change**	**Significant decrease**	**Mixed responses**	
Soil organic carbon storage	12 plus two meta-analyses	24	1	0	Strong (Data were based on results of field experiments)
Aggregate stability	7	10	2	0	
Bulk density	1	20	2		
Total porosity	5	6	0	0	
Hydraulic conductivity	0	1	4	0	
Earthworm population	3	9	0	0	
Crop yield	0	4	0	0	

Table 5.2: Impacts of specific cover crops on soil health parameters (SOC = soil organic carbon). Number of articles = 32.

Broad intervention	**Specific intervention**	**Soil health parameter**	**Effect of intervention (number of datasets)**	**Quality of evidence**	**Source of evidence (Country and number of studies)**
Cover crop	Radish (*Raphanus sativus*) cover	SOC storage	No significant effect (3)	Strong (Data collected from field experiments)	Denmark (1), The Netherlands (1), USA (1)
		Aggregate stability	No significant effect (2)		
		Bulk density	No significant effect (1)		
		Crop yield	No significant effect (1)		

	Rye (*Secale cereale*) cover	SOC storage	No significant effect (8), Significant increase (3)	Strong (Data collected from field experiments)	USA (9), Canada (2), Poland (2), Austria (1), Italy (1), Ireland (1)
		Aggregate stability	No significant effect (3), Significant increase (3), Significant reduction (2)		
		Bulk density	No significant effect (5)		
		Total porosity	No significant effect (1)		
		Hydraulic conductivity	Significant reduction (1)		
		Number of earthworms	No significant effect (2), Significant increase (1)		
		Crop yield	No significant effect (1)		
	Wheat (*Triticum aestivum*) cover	SOC storage	No significant effect (2)	Strong (Data collected from field experiments)	USA (2)
	Ryegrass (*Lolium perenne*) cover	SOC storage	Significant reduction (1), No significant effect (1)	Strong (Data collected from field experiments)	The Netherlands (1), USA (1), Canada (1), Ireland (1)
		Bulk density	No significant effect (1)		

		Aggregate stability	No significant effect (1), Significant increase (1)		
		Number of earthworms	No significant effect (1)		
		Number of earthworms	No significant effect (1)		
	Clover (e.g. *Trifolium repens*)	SOC storage	No significant effect (1), Significant increase (3)	Strong (Data collected from field experiments)	The Netherlands (1), France (1), Italy (1), Spain (1), Poland (1)
		Bulk density	No significant effect (3)		
		Aggregate stability	No significant effect (1)		
		Total porosity	No significant effect (1)		
	Vetch (e.g. *Vicia sativa*)	SOC storage	No significant effect (1)	Strong (Data collected from field experiments)	The Netherlands (1), Poland (1) Austria (1),
		Total porosity	No significant effect (1)		
		Hydraulic conductivity	Significant reduction (1)		
	Fescue (*Festuca* spp.)	SOC storage	No significant effect (1)	Strong (Data collected from field experiments)	France (2), Spain (1)
		Aggregate stability	Significant increase (2)		
		Bulk density	No significant effect (1)		
		Total porosity	Significant increase (1)		
		SOC storage	Significant increase (1)		USA (1)

	Lentil (e.g. Lens culinaris)	Bulk density	No significant effect (1)	Strong (Data collected from field experiments)	
	Pea (e.g. *Pisum sativum*)	SOC storage	No significant effect (1)	Strong (Data collected from field experiments)	USA (1), Ireland (1)
		Number of earthworms	Significant increase (1)		
	Triticale (*Triticosecale*)	SOC storage	Significant increase (3)	Strong (Data collected from field experiments)	USA (3)
		Aggregate stability	Significant increase (1)		
		Bulk density	No significant effect (2), Significant reduction (1)		
	Oat (*Avena sativa*)	SOC storage	No significant effect (2)	Strong (Data collected from field experiments)	Poland (1), USA (2), Ireland (1)
		Aggregate stability	No significant effect (1)		
		Total porosity	No significant effect (1)		
		Bulk density	No significant effect (3)		
		Number of earthworms	Significant increase (1)		
		Crop yield	No significant effect (1)		
	Mustard (e.g. *Sinapis alba*)	Total porosity	No significant effect (1)	Strong (Data collected from field experiments)	Poland (3), Austria (1), Ireland (1)
		Hydraulic conductivity	Significant reduction (1)		

		Number of earthworms	No significant effect (1)		
	Phacelia (*Phacelia tanacetifolia*)	Total porosity	Significant increase (1)	Strong (Data collected from field experiments)	Poland (1), Austria (1), Ireland (1)
		Hydraulic conductivity	Significant reduction (1)		
		Number of earthworms	No significant effect (1)		
	Buckwheat (*Fagopyrum esculentum*)	Bulk density	Significant increase (1)	Strong (Data collected from field experiments)	Poland (2)
		Total porosity	Significant increase (1)		
	Sunflower (*Helianthus annuus*)	Total porosity	No significant effect (1)	Strong (Data collected from field experiments)	Poland (1)
	Bird's-foot-trefoil (*Lotus corniculatus*)	Total porosity	Significant increase (1)	Strong (Data collected from field experiments)	France (1)
	Alfalfa (*Medicago sativa*)	Total porosity	Significant increase (1)	Strong (Data collected from field experiments)	France (1)
	Oilseed rape (*Brassica napus*)	SOC storage	No significant effect (1)	Strong (Data collected from field experiments)	Estonia (1), USA (1), Poland (1), Ireland (1), UK (1)
		Aggregate stability	No significant effect (1)		
		Bulk density	No significant effect (1)		

		Number of earthworms	No significant effect (3)		
		Crop yield	No significant effect (1)		
	Barley (*Hordeum vulgare*)	SOC storage	Significant increase (1)	Strong (Data collected from field experiments)	Canada (1), Spain (1)
		Aggregate stability	No significant effect (1)		
		Bulk density	No significant effect (1)		
	Sunn hemp (*Crotalaria juncea*)	SOC storage	Significant increase (1)	Strong (Data collected from field experiments)	USA (1)
		Bulk density	Significant reduction (1)		
		Hydraulic conductivity	No significant effect (1)		
	Millet (*Panicum miliaceum*)	Bulk density	No significant effect (1)	Strong (Data collected from field experiments)	Poland (1)
		Total porosity	Significant increase (1)		
	Not specified	SOC storage	Significant increase	Strong (Data based on meta-analysis)	Meta-analysis of data from the Mediterranean climate zone (40°N - 40°S
	Not specified	SOC storage	No significant effect (1)	Strong (Data collected from field experiments)	USA (1)
	Not specified	SOC storage	Significant increase	Strong (Data based on meta-analysis)	Meta-analysis of data from Europe (8), North America (12), South America (4) and Asia (5)

Table 5.3: Study location.

Country	Number of studies
Denmark	1
USA	14
Canada	2
The Netherlands	1
France	2
Poland	3
Italy	1
Spain	2
Ireland	1
United Kingdom	1
Estonia	1
Austria	1
Mixed (different countries)	2

Table 5.4: Study type, scale and soil depth sampled.

Study type	**Number of studies**
Control versus treatment (i.e. presence of cover crops versus absence of cover crops)	32
Scale	
Field scale with varied plot sizes	32
Soil depth (cm)	
0-30	31
Above 30	1

Table 5.5: Duration of intervention.

Time since start of cover cropping (years)	Number of studies
1-10	27
11-20	3
21-30	1
31-60	1
1 to 60 (i.e. studies that investigated fields under different duration of management)	0
Above 60	0

Appendix 6: Data on land use change – conversion of agricultural land to woodland

Table 6.1: Overall effects of converting agricultural land to woodland on soil health parameters (n=25)

Soil health parameter	**Response of soil heath parameters to the conversion of agricultural land to woodland (number of datasets)**				**Strength of evidence**
	Significant increase	**No significant change**	**Significant decrease**	**Mixed responses**	
Soil organic carbon storage	6	13	11	0	Strong (All data, except one modelling study, were based on results of field experiments)
Aggregate stability	0	1	0	0	
Bulk density	2	10	5	0	
Total porosity	2	0	0	0	
Hydraulic conductivity	3	0	0	0	
Infiltration	1	0	0	0	

Table 6.2: Impacts of converting agricultural land to woodland on soil health (SOC = soil organic carbon). Number of studies = 25.

Broad intervention	**Specific intervention**	**Soil health parameter**	**Effect of intervention (number of datasets)**	**Quality of evidence**	**Source of evidence (country and number of studies)**
Conversion to woodland	Grassland to woodland (18)	SOC storage	Woodland higher than grassland (2); no significant effect (11); woodland lower than grassland (9)	Strong (data collected from field experiments (17), modelling (1))	Canada (1), England (1), Ireland (3), New Zealand (10), Scotland (1), Wales (1), multiple (Austria, Denmark, Germany, Ireland, Italy, Lithuania, Netherlands, Scotland, Sweden, Switzerland) (1)
		Bulk density	Woodland higher than grassland (2); no significant effect (8); woodland lower than grassland (3)		
		Water stable aggregates	No significant effect (1)		
		Infiltration	Woodland higher than grassland (1)		
		Hydraulic conductivity	Woodland higher than grassland (1)		
	Arable land to woodland (9)	SOC storage	Woodland higher than arable (4); no significant effect (2); woodland lower than arable (2)	Strong (data collected from field experiments (9))	Canada (1), Czech Republic (1), Italy (1), Poland (2), Scotland (1), Sweden (1), USA (1), multiple (Austria, Denmark, Germany, Ireland, Italy, Lithuania, Netherlands, Scotland, Sweden, Switzerland) (1)
		Bulk density	No significant effect (2); woodland lower than arable (2)		
		Hydraulic conductivity	Woodland higher than arable (2)		
		Porosity	Woodland higher than arable (2)		

Table 6.3: Study location (n=25)

Country	**n**
Canada	1
Czech Republic	1
England	1
Ireland	3
Italy	1
New Zealand	10
Poland	2
Scotland	2
Sweden	1
Wales	1
USA	1
Multiple (Austria, Denmark, Germany, Ireland, Italy, Lithuania, Netherlands, Scotland, Sweden, Switzerland)	1

Table 6.4: Summary of study type and scale (n=25)

Study type	**n**
BACI	3
Control vs. treatment	20
Comparative	1
Modelling	1
Scale	
Plot	15
Site	8
Field	1
Unknown	1

Table 6.5: Details of afforestation (n=25)

Previous land use	**n**
Arable	9
Pasture	9
Grassland	9
Time since afforestation	
0-10	6
11-20	14
21-30	9
31-60	7
61+	3
Main tree species	
Conifer	16
Ash	3
Other	5

Appendix 7: Data on Hedges

Table 7.1: Overall effects of hedges on soil health parameters (n=12).

Soil health parameter	**Response of soil heath parameters to hedges (number of datasets)**				**Strength of evidence**
	Significant increase	**No significant change**	**Significant decrease**	**Mixed responses**	
Soil organic carbon storage	6	1	1	0	Moderate (about 50% of data were based mostly on field experiments with no clearly defined control as well as results from modelling studies)
Aggregate stability	2	0	0	0	
Bulk density	0	1	3	0	
Infiltration	0	1	0	0	
Hydraulic conductivity	1	0	0	0	
Earthworm population	3	2	0	0	

Table 7.2: Impacts of hedges on soil health (SOC = soil organic carbon). Number of studies = 12.

Intervention	Soil health parameter	Effect of intervention (number of datasets)	Quality of evidence	Source of evidence (country and number of studies)
Hedges	SOC storage	Higher in hedgerow (6); no significant effect (1); lower in hedgerow (1); significance not reported (4)	Moderate (data collected from field experiment (5), field observation (5), modelling (2))	Canada (1), France (5), Italy (1), USA (1), UK (2), Denmark (1), Review of temperate region (1)
	Bulk density	No significant effect (1); lower in hedgerow (3)		
	Water stable aggregates	Higher in hedgerows (2)		
	Infiltration	No significant effect (1)		
	Hydraulic conductivity	Higher in hedgerows (1)		
	Earthworms	Higher in hedgerows (3); no significant effect (2)		

Table 7.3: Study location (n=12)

Country	**n**
Canada	1
France	5
Italy	1
UK	2
Denmark	1
USA	1
Different countries in temperate region	1

Table 7.4: Summary of study type and scale (n=12)

Study type	**n**
Observational (no clearly defined control)	4
Control vs. treatment	5
Comparative	1
Modelling	2
Scale	
Plot	3
Farm	1
Field	6
Landscape	2

Appendix 8: Data on Grass leys in arable systems

Table 8.1: Overall effects of leys on soil health parameters (n=15).

Soil health parameter	Response of soil heath parameters to leys (number of datasets)				Strength of evidence
	Significant increase	No significant change	Significant decrease	Mixed responses	
Soil organic carbon storage	14	4	0	0	Strong (Data were based on results of field experiments)
Aggregate stability	1	0	0	0	
Bulk density	0	1	1	0	
Water holding capacity	0	1	0	0	
Earthworm population	2	0	0	0	
Earthworm activity	1	0	0	0	
Crop yield	1	0	0	0	

Table 8.2: Impacts of leys on soil health (SOC = soil organic carbon). Number of articles = 15.

Broad intervention	Specific intervention	Soil health parameter	Effect of intervention (number of datasets)	Strength of evidence	Source of evidence (Country and number of studies)
Introduce leys in arable rotation	Grass leys	SOC storage	Significant increase (8), No significant effect (1)	Strong (Data collected from field experiments)	Sweden (3), France (2), UK (3), Belgium (1)
		Bulk density	No significant effect (1)		
		Water holding capacity	No significant effect (1)		
		Number of earthworms	Significant increase (1)		
		Crop yield	Significant increase (1)		
	Grass-clover leys	SOC storage	Significant increase (6), No significant effect (3)	Strong (Data collected from field experiments)	Sweden (3), UK (4), Switzerland (1)
		Bulk density	Significant reduction (1)		
		Aggregate stability	Significant increase (1)		
		Number of earthworms	Significant increase (1)		
		Earthworm activity	Significant increase (1)		

Table 8.3: Study location.

Country	Number of studies
Sweden	5
France	2
United Kingdom	6
Belgium	1
Switzerland	1

Table 8.4: Study type, scale and soil depth sampled.

Study type	Number of studies
Control versus treatment (i.e. leys in arable rotation versus arable rotation without leys)	15
Scale	
Field scale with varied plot sizes	15
Soil depth (cm)	
0-30	15
Above 30	0

Table 8.5: Duration of intervention.

Time since start of ley introduction (years)	Number of studies
1-10	6
11-20	1
21-30	0
31-60	6
1 to 60 (i.e. studies that investigated fields under different duration of management)	1
Above 60	1

Appendix 9: Data on Addition of organic amendments

Table 9.1: Overall effects of organic amendment on soil health parameters (n=26).

Soil health parameter	**Response of soil heath parameters to organic amendments (number of datasets)**				**Strength of evidence**
	Significant increase	**No significant change**	**Significant decrease**	**Mixed responses**	
Soil organic carbon storage	20	9	0	0	Strong (Data were based on results of field experiments)
Aggregate stability	10	2	0	0	
Bulk density	0	2	1	0	
Earthworm population	7	2	1	0	

Table 9.2: Effects of organic amendment on soil health parameters (SOC = soil organic carbon). Number of studies = 26.

Broad intervention	**Specific intervention**	**Soil health parameter**	**Effect of intervention (number of datasets)**	**Quality of evidence**	**Source of evidence (Country and number of studies)**
Organic amendment	Corn straw/residue retention or incorporation	Earthworm population	Significant increase (2), No significant effect (1)	Strong (Data collected from field experiments)	Canada (2), Italy (1), USA (7)
		SOC storage	Significant increase (3), No significant effect (3)		
		Aggregate stability	Significant increase (4), No significant effect (1)		
		Bulk density	No significant effect (2)		
	Wheat residue retention or incorporation	SOC storage	Significant increase (3), No significant effect (2)	Strong (Data collected from field experiments)	Canada (1), USA (2), France (1), UK (1)
		Aggregate stability	Significant increase (2), No significant effect (1)		
		Bulk density	Significant reduction (1)		
	Barley straw/residue retention or incorporation	SOC storage	No significant effect (2)	Strong (Data collected from field experiments)	Canada (1)
	Oat residue retention or incorporation	Aggregate stability	Significant increase (1)	Strong (Data collected from field experiments)	France (1)

	Miscanthus residue retention or incorporation	Aggregate stability	Significant increase (1)	Strong (Data collected from field experiments)	France (1)
	Mixed crop residue retention or incorporation	SOC storage	Significant increase (6)	Strong (All data collected from field experiments. Data reported in three studies were based on meta-analysis of previously published experimental data)	Canada (1), Switzerland (1), Italy (2), Review of Europe and north America (3)
		Earthworm population	Significant increase (1)		
		Aggregate stability	Significant increase (1)		
	Cattle slurry addition	SOC storage	Significant increase (1), No significant effect (2)	Strong (All data collected from field experiments. Data reported in one study were based on meta-analysis of previously published experimental data)	Italy (2), Review of Europe (1)
		Earthworm population	No significant effect (1)		
	Farmyard manure addition	SOC storage	Significant increase (4)	Strong (All data collected from field experiments. Data reported in one study were based on meta-analysis of previously published experimental data)	Italy (2), Switzerland (1), Review of Europe (1)
		Earthworm population	Significant increase (2)		

	Compost addition	SOC storage	Significant increase (1)	Strong (All data collected from field experiments. Data reported in one study were based on meta-analysis of previously published experimental data)	Germany (1), Review of Europe (1)
		Earthworm population	Significant increase (1)		
	Sewage sludge addition	SOC storage	Significant increase (2)	Strong (Data collected from field experiments)	Spain (1)
		Aggregate stability	Significant increase (1)		
	Biosolids addition	Earthworm population	Significant increase (1), Significant reduction (1)	Strong (Data collected from field experiments)	Canada (1)

Table 9.3: Study location.

Country	Number of studies
USA	8
Switzerland	1
Canada	5
France	1
Italy	3
Spain	1
Germany	1
United Kingdom	1
Mixed (different countries)	5

Table 9.4: Study type, scale and soil depth sampled.

Study type	Number of studies
Control versus treatment (i.e. organic amendment versus no organic amendment)	26
Scale	
Field scale with varied plot sizes	26
Soil depth (cm)	
0-30	26
Above 30	0

Table 9.5: Duration of intervention.

Time since start of organic amendment (years)	Number of studies
1-10	10
11-20	5
21-30	4
31-60	2
1 to 60 (i.e. studies that investigated fields under different duration of management)	5
Above 60	0

Appendix 10: Data on leaving stubble overwinter

Table 10.1: Overall effects of overwinter stubble on soil health parameters (n=10).

Soil health parameter	**Response of soil heath parameters to overwinter stubble (number of datasets)**				**Strength of evidence**
	Significant increase	**No significant change**	**Significant decrease**	**Mixed responses**	
Soil organic carbon storage	4	4	0	0	Strong (Data were based on results of field experiments)
Aggregate stability	1	2	0	0	
Bulk density	0	3	0	0	
Earthworm population	4	3	0	0	
Crop yield	1	0	0	0	

Table 10.2: Impacts of overwinter stubble on soil health (SOC = soil organic carbon). Number of articles = 10.

Broad intervention	**Specific intervention**	**Soil health parameter**	**Effect of intervention (number of datasets)**	**Quality of evidence**	**Source of evidence (Country and number of studies)**
Overwinter stubble	Stubble retention vs stubble burning	SOC storage	Significant increase (4), No significant effect (2)	Strong (Data collected from field experiments)	Australia (7)
		Earthworm biomass	Significant increase (1)		
		Aggregate stability	Significant increase (1), No significant effect (2)		
		Bulk density	No significant effect (1)		
		Number of earthworms	Significant increase (4)		
		Crop yield	Significant increase (1), No significant effect (1)		
	Stubble retention vs stubble removal	SOC storage	No significant effect (2)	Strong (Data collected from field experiments)	Finland (2), USA (1)
		Bulk density	No significant effect (2)		
		Number of earthworms	No significant effect (3)		

Table 10.3: Study location.

Country	Number of studies
Finland	2
Australia	7
USA	1

Table 10.4: Study type, scale and soil depth sampled.

Study type	Number of studies
Control versus treatment (i.e. stubble retention versus stubble burning or stubble removal)	10
Scale	
Field scale with varied plot sizes	10
Soil depth (cm)	
0-30	9
Above 30	1

Table 10.5: Duration of intervention.

Time since start of overwinter stubble (years)	Number of studies
1-10	4
11-20	1
21-30	2
31-60	2
1 to 60 (i.e. studies that investigated fields under different duration of management)	1
Above 60	0

Appendix 11: Data on Tillage practice

Table 11.1: Overall effects of conservation tillage on soil health parameters (n=90).

Soil health parameter	**Response of soil heath parameters to conservation tillage (number of datasets)**				**Strength of evidence**
	Significant increase	**No significant change**	**Significant decrease**	**Mixed responses**	
Soil organic carbon storage	83	48	0	1	Strong (Data were based on results of field experiments)
Aggregate stability	60	28	3	0	
Bulk density	43	80	27	0	
Total porosity	6	5	4	0	
Infiltration	17	1	0	0	
Hydraulic conductivity	12	19	11	0	
Earthworm population	16	10	2	1	

Table 11.2: Impacts of reduced/no tillage on soil health (SOC = soil organic carbon). Number of articles = 90.

Broad intervention	**Specific intervention**	**Control intervention**	**Soil health parameter**	**Effect of intervention (number of datasets)**	**Strength of evidence**	**Source of evidence (Country and number of studies)**
Conservation tillage	No tillage/direct drilling/zero tillage	Harrowing	SOC storage	No significant effect (2)	Strong (Data collected from field experiments)	Denmark (2), Norway (1)
			Aggregate stability	Significant increase (2), No significant effect (1)		
			Bulk density	No significant effect (1)		
			Porosity	No significant effect (1)		
			Earthworm population	No significant effect (1)		
	No tillage/direct drilling/zero tillage	Ploughing	SOC storage	Significant increase (7), No significant effect (7)	Strong (Data collected from field experiments)	USA (2), Croatia (1), Lithuania (1), Germany (1), Denmark (1), Norway (1)
			Bulk density	No significant effect (2), Significant reduction (1)		
			Aggregate stability	Significant increase (3)		
			Porosity	Significant increase (1)		
			Earthworm population	Significant increase (6), No significant effect (2)		

	No tillage/direct drilling/zero tillage	Chisel ploughing	SOC storage	Significant increase (11), No significant effect (1)	Strong (Data collected from field experiments)	USA (9), Switzerland (1), Canada (3),
			Bulk density	Significant increase (3), No significant effect (20), Significant reduction (2)		
			Total porosity	Significant increase (1), Significant reduction (1)		
			Aggregate stability	Significant increase (5), No significant effect (9), Significant reduction (1)		
			Earthworm population	Significant increase (2), Significant reduction (1)		
			Infiltration	Significant increase (1)		
	No tillage/direct drilling/zero tillage	Mouldboard Ploughing	SOC storage	Significant increase (16), No significant effect (5), Mixed effect (1)	Strong (Data collected from field experiments; the data in one study were extracted from previously	Denmark (1), USA (6), Germany (2), Switzerland (2), Italy (2), Greece (1), France (1), Canada (3),
			Aggregate stability	Significant increase (4), No significant effect (1)		

			Bulk density	Significant increase (4), No significant effect (3)	published results of field experiments)	Global review (1),
			Earthworm population	Significant increase (1), No significant effect (1)		
			Total porosity	Significant increase (3), Significant reduction 1)		
			Hydraulic conductivity	Significant reduction (1)		
	No tillage/direct drilling/zero tillage	Stubble mulch tillage	Aggregate stability	Significant reduction (1)		USA (1),
			Infiltration	No significant effect (1)		
	No tillage/direct drilling/zero tillage	Conventional tillage	SOC storage	Significant increase (28), No significant effect (18)	Strong (Data collected from field experiments; the data in seven studies were extracted from previously published results of field experiments)	USA (10), Spain (4), UK (1), Switzerland (1), Italy (3), Czech (1), Canada (6), France (1), Lithuania (1), Finland (1), Germany (1), Europe-wide (1), Global review (5)
			Bulk density	Significant increase (33), No significant effect (39), Significant reduction (13)		
			Aggregate stability	Significant increase (39), No significant effect (14), Significant reduction (1)		

			Infiltration	Significant increase (15)		
			Hydraulic conductivity	Significant increase (11), No significant effect (16), Significant reduction (8)		
			Earthworm population	Significant increase (5), No significant effect (1), Mixed effects (1)		
			Total porosity	No significant effect (1), Significant reduction (1)		
	Minimum/Reduced tillage	Mouldboard Ploughing	Bulk density	Significant increase (3), No significant effect (10), Significant reduction (10)	Strong (Data collected from field experiments)	France (1), Germany (4), The Netherlands (1), Poland (1), Denmark (1), Belgium (1), Switzerland (1), Finland (1), Italy (1), USA (1)
			SOC storage	Significant increase (14), No significant effect (11)		
			Aggregate stability	Significant increase (5)		
			Earthworm population	Significant increase (1), No significant effect (2), Significant reduction (1)		

			Hydraulic conductivity	Significant reduction (1)		
			Total porosity	No significant effect (2)		
	Minimum/Reduced tillage	Conventional tillage	SOC storage	Significant increase (7), No significant effect (4)	Strong (Data collected from field experiments; the data in one study were extracted from previously published results of field experiments)	Switzerland (1), Germany (2), Portugal (1), Finland (1), Norway (2), Spain (2), Austria (1), Italy (1), Ireland (1), Czech (1), Lithuania (1), Global review (1), USA (2)
			Bulk density	No significant effect (5), Significant reduction (1)		
			Hydraulic conductivity	Significant increase (1), No significant effect (3), Significant reduction (1)		
			Aggregate stability	Significant increase (2), No significant effect (3)		
			Earthworm population	Significant increase (1), No significant effect (3)		
			Total porosity	Significant increase (1), No significant effect (1), Significant reduction (1)		
			Infiltration	Significant increase (1)		

Table 11.3: Study location

Country	Number of studies
Denmark	3
USA	24
Croatia	1
Lithuania	2
Germany	8
Switzerland	4
Canada	12
Italy	7
Poland	1
Belgium	1
Austria	1
Greece	1
France	2
Spain	4
UK	2
Czech	1
Finland	2
The Netherlands	2
Portugal	1
Norway	3
Ireland	1
Multiple countries	7

Table 11.4: Study type, scale and soil depth sampled

Study type	**Number of studies**
Control versus treatment (i.e. reduced or no tillage versus conventional tillage)	89
Before and after comparison	1
Scale	
Field scale with varied plot sizes	90
Soil depth (cm)	
0-30	87
Above 30	3

Table 11.5: Duration of intervention

Duration of tillage/no tillage treatment (years)	Number of studies
1-10	36
11-20	26
21-30	5
31-60	6

1 to 60 (i.e. studies that investigated fields under different duration of tillage, for example 5, 20 and 30 years)	18
Above 60	0