Scotland's Rural College

A high-level scoping review - Farming, greenhouse gas emissions and carbon storage: cereals and oilseeds

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A high-level scoping review

Farming, greenhouse gas emissions and carbon storage: cereals and oilseeds

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1. Abstract

This high-level scoping project aimed to inform the design and development of the Evidence for Farming Initiative (EFI). It provided information focused on the 'net zero' agenda that will allow prototype products and services to assist decision-makers seeking to reduce greenhouse gas (GHG) emissions in arable farming systems. A reduction in net GHG emissions within combinable cropping systems (whether assessed per unit of output, per unit of land area used, or at a national level) will be achieved most effectively by the implementation of on-farm interventions that increase productive efficiency and carbon storage, and produce materials/energy for the green economy.

The UK research landscape underpinning the measurement or mitigation of GHG emissions in UK cropping systems was found to be widespread and diverse, with research teams often working in collaboration (in a range of configurations, depending on the research question under investigation). The links between bio-economy research and practical agronomic application appeared to be the least well developed; in addition, much of the underpinning work on renewable energy and fossil fuel replacement is not directly targeted at the agriculture sector (which is likely to benefit from ongoing research for construction and road haulage). However, there are relevant international collaborations in place, including informal knowledge sharing, via academic societies, as well as through formal research collaborations.

There is a significant body of published research evidence that considers the impact of many of the potential interventions proposed to reduce net GHG of direct relevance to UK arable farming. For several interventions, there were a number of specific systematic reviews. Bringing together evidence, systematic evidence synthesis is a relatively new process and tends to have been applied where the interventions are new or where there has been some dispute/uncertainty about their impact. For other interventions, the underlying principles were well established – such as carbon storage in trees, and change in GHG balance in drained vs undrained wetlands – but detailed synthesis of evidence directly relevant to the application of the intervention in UK cropping systems was either not available or covered only part of the GHG balance. As part of the pilot development of EFI, this scoping review has confirmed that there is a body of high quality reviews linking the following interventions to net GHG in combinable cropping systems:

- Optimising nitrogen (N) addition and avoiding N excess
- Growing ground cover in leaching-risk periods, and the use of catch and cover crops (considered together)
- Reducing intensity of cultivation
- Use of manures and composts
- Use of biosolids and industrial wastes
- Use of controlled-release fertiliser/inhibitors
- Use of biochar

However, there is lack of direct evidence for cropping systems for interventions relating to the generation of renewable energy, replacement of fossil fuel energy and producing materials/energy for the green economy.

A range of indicators are currently used by Defra (and the other devolved governments) to measure progress towards net zero in the farming sector. Several GHG benchmarking tools are also available to estimate net GHG at farm/enterprise level. Such data are increasingly being required within supply chains. A key challenge for farm benchmarking will be the provision of sufficient and appropriate background data against which participating farms can robustly benchmark their performance. However, it is also important to consider GHG mitigation measures within a wider sustainability framework, particularly because of the trade-offs that may result, For example, the impact of use of crops supplying alternative biomaterials on ecological interactions (e.g. pollinators), herbicide and pesticide use.

The review has confirmed that EFI needs to be underpinned by a clear and transparent theory of change that will allow EFI to identify where, how and when to intervene to impact change in agricultural systems to deliver mitigation of net GHG. Science and the evidence-base available for synthesis and systematic review is designed to answer “why does it work” questions and draw out common principles – hence the value of meta-analysis. However, for farmers the most important question is “will it work for me” and EFI will need an underpinning model that allows it to bring together evidence from science and practice effectively.

2. Background

The Food and Drink Sector Council's Agricultural Productivity Working Group report in February 2020 (www.fdf.org.uk/publicgeneral/APWG-report-feb20.pdf) recommended development of the Evidence for Farming Initiative (EFI). EFI is based on principles underpinning the What Works network, which currently identifies and shares best practice across a range of public organisations in the UK. EFI will be industry-facing, focussing on the collation of evidence-based best practice recommendations within Farming, commercial testing of advice to provide quality assurance, and wide-scale dissemination of information for use by decision-makers. AHDB's ambition is, over time, for EFI to:

- identify the best available evidence for how farmers, growers, advisers and other decision-makers can bring about sustainable businesses operating in a sustainable sector
- address gaps in the evidence base by conducting and supporting primary research and by commissioning and undertaking evidence syntheses
- translate evidence into accessible, actionable materials
- support decision makers in using evidence to improve the effectiveness and cost-effectiveness of agricultural practice
- identify data owners and potential research partners to ensure that EFI is sustained for the long-term.

AHDB are piloting EFI with an initial focus on the 'Net Zero' agenda. The results of this scoping review for combinable crops (together with reviews for other sectors reported separately) will allow EFI to prototype products and services to assist decision-makers seeking to reduce GHG emissions now and over the next decade. These reviews will therefore:

- support initial decision-making on the overall setting of direction for EFI (i.e. where, across the Net Zero agenda, the Initiative might target its early efforts);
- help EFI identify areas and topics on which it might develop evidence-translation materials for use by farmers, growers and other decision-makers;
- after the overall direction has been set, support AHDB in commissioning some pieces of more focused evidence-review activity that will support the development of EFI products and services;
- support EFI to identify areas where collaboration with relevant stakeholders, interested parties and new technology developers can leverage greater co-operation or value from datasets to drive innovation and the evidence base.

The scope for this review includes both changes to farming methods for existing combinable crops (for example by reduction in tillage intensity), changes to crops or rotations (e.g. replacing wheat with triticale) and changes to cropping systems (for example by adoption of conservation agriculture), together with changes to the outputs of individual farm businesses (for example, through the production of biomass and bioenergy). The review will identify the current evidence of what works to reduce net GHG emissions in current practice and will also draw insights from existing research into the potential for improvements over a ten-year time scale.

3. Project aim and objectives

This short high-level scoping project aims to inform the design and development of the Evidence for Farming Initiative (EFI) by underpinning the initial pilot focused on the 'Net Zero' agenda that will prototype products and services to assist decision-makers seeking to reduce greenhouse gas (GHG) emissions now and over the next decade. This will be achieved by:

- Developing an overall picture of the evidence landscape for 'net zero' arable farming by identifying existing research syntheses and agglomerations of research evidence, key farm performance indicators and associated benchmarks, new data-driven approaches that could enable greater insight, together with gaps in the evidence base.
- Carrying out a scoping review of research studies and evidence syntheses to identify what works now (and the most likely innovations that will work over the next decade) to reduce GHG emissions and increase carbon storage for farms growing cereals and oilseeds. The review will:
    - highlight the areas and topics where EFI might develop evidence-translation materials rapidly for use by farmers, growers and other decision-makers;
    - show where more focused evidence-review activity is needed to underpin the development of EFI products and services;
    - outline where collaboration will leverage greater co-operation or value from datasets to drive innovation and increase the evidence base; and,
    - identify any remaining gaps in the evidence base that EFI might seek to plug through the commissioning of primary research.

4. Mitigating GHG emissions in UK arable agriculture – evidence landscape

4.1. GHG emissions in UK arable agriculture - background

Assessments of the contribution of agriculture, forestry and other land use activities to global GHG emissions (1990-2012; Tubiello et al. 2015) show that in 2010 emissions from agriculture (crop and livestock production) contributed 11.2 ± 0.4% of total GHG emissions, compared to 10.0 ± 1.2% from land use (land use, land use change and forestry, including deforestation). Methane emissions which contribute c. 30% of this total are dominantly associated with ruminant livestock, manure handling and flooded rice paddies. However, nitrous oxide (N_2O) is the main greenhouse gas emitted in the arable cropping sector; this arises from microbial activity following application of nitrogen (N) in fertilisers / organic materials. Inputs, such as fertiliser, also have high embedded energy cost (and hence indirect GHG emissions) arising from their manufacture. Hence 50-60% of the GHG emissions on an arable farm can often be directly linked to N fertiliser use. Direct carbon dioxide (CO_2) emissions from on-farm energy use (mainly diesel from field operations in the arable sector) can be 15-20% of the farm GHG emissions. Changes in soil organic matter – whether losses in cultivated peat soils or gains where arable soils are planted with woodland – are accounted for in the Land Use, Land Use Change and Forestry (LULUCF) inventory. However in arable soils where cultivation has led to carbon (C) losses over the long-term, there may be opportunities to increase soil C storage through modification of practices within cropping systems and also to integrate a higher proportion of woodland into lowland systems, thus also increasing C storage and leading to net negative GHG emissions for some land management practices. Cropping systems are also well placed to provide inputs to the bioeconomy (whether biomaterials or bioenergy) that can reduce the need for fossil fuels elsewhere in the economy.

Reducing agricultural GHG emissions by at least 100% of 1990 levels by 2050 is written into law as part of the UK Climate Change Act. The Clean Growth Strategy, overseen by the Department for Business, Energy and Industrial Strategy, BEIS, published in 2017, set an interim target of 57% GHG reduction by 2032. The Welsh and Northern Ireland Administrations have established plans to identify how agriculture can reduce emissions. Scottish Government has developed the Farming for a Better Climate website which is designed to encourage voluntary uptake through the provision of information on win-win actions and has plans to introduce regulation if sufficient progress is not made to increase nitrogen use efficiency. In England and Wales, Defra have supported a voluntary industry-led approach by providing scientific data to help understand the factors that drive GHG production and identifying the actions that can help to reduce it. The National Farmers Union (NFU) worked with fourteen other organisations representative of the breadth of the agricultural industry in England, including AHDB, to develop the Agricultural Industry GHG Action Plan. The GHGAP review 2016 (Defra 2017) found that it helped to drive the uptake of mitigation methods and delivered just under 1/3 of the target reduction in emissions, but that much more remained to be done. However, the 2018 progress report to Parliament by the Committee on Climate Change made sobering reading, reporting “virtually no change in agricultural emissions since 2008”. In 2019, NFU developed a vision for ‘Net Zero’ by 2040. Defra are currently reviewing how to align steps for GHG mitigation on farm with the changed structures of farm support (Environmental Land Management scheme) post-Brexit.

For this scoping review, we have worked with AHDB, building on the NFU 3-pillar approach, and agreed a taxonomy of interventions suggested to reduce net GHG emissions within combinable cropping systems (Figure 1). Such changes are likely to take place within the context of larger framework of on-going changes that will affect combinable cropping systems*, inter alia* diet change, food waste reduction, land use change and trade. For example a significant dietary shift towards plant-based foods would be expected to lead to a growth in the land area of the arable sector to some extent, which could increase overall emissions, even where productivity efficiency was improved. Smith et al. (2013) suggested that the primary focus for immediate implementation should be interventions that support the production of more agricultural product per unit of input. However, here we consider that a reduction in net GHG emissions within combinable cropping systems (whether assessed per unit of output, per unit of land area used, or at a national level) will be achieved most effectively by addressing all 3 objectives in parallel:

Objective 1: Increasing productive efficiency

- 1.1 Removing constraints to production
- 1.2 Improving N use efficiency and reducing N (and other nutrient) losses
- 1.3 Improving energy efficiency

Objective 2: Increasing carbon storage

- 2.1 Changing land use and management
- 2.2 Adopting long-term practices to increase soil carbon storage in the field
- 2.3 Peatland /wetland restoration
- 2.4 Increasing trees and hedgerows

Objective 3: Boosting the green economy

- 3.1 Generating renewable energy
- 3.2 Replacing fossil fuels
- 3.3 Delivering products to the bioeconomy

The interventions identified for consideration in the Scoping Review are not necessarily a complete list, though we have worked carefully in consultation with AHDB and other stakeholders to ensure that the majority of proposed interventions are captured within the taxonomy (Figure 1). In some cases, we have shown examples of how an intervention may be comprised of a number of practices. It should also be noted that some system changes may be made up of a number of separate interventions e.g. adoption of conservation agriculture would include both “Catch and cover cropping” and “Reducing intensity of cultivation” and may also include “Integrating / optimising N fixation in the rotation” as well as other interventions.

If a taxonomy was drawn up for another over-arching aim e.g. Improving water quality, we would expect that whilst the objectives and structure of the taxonomy might change, some of the same interventions would appear.

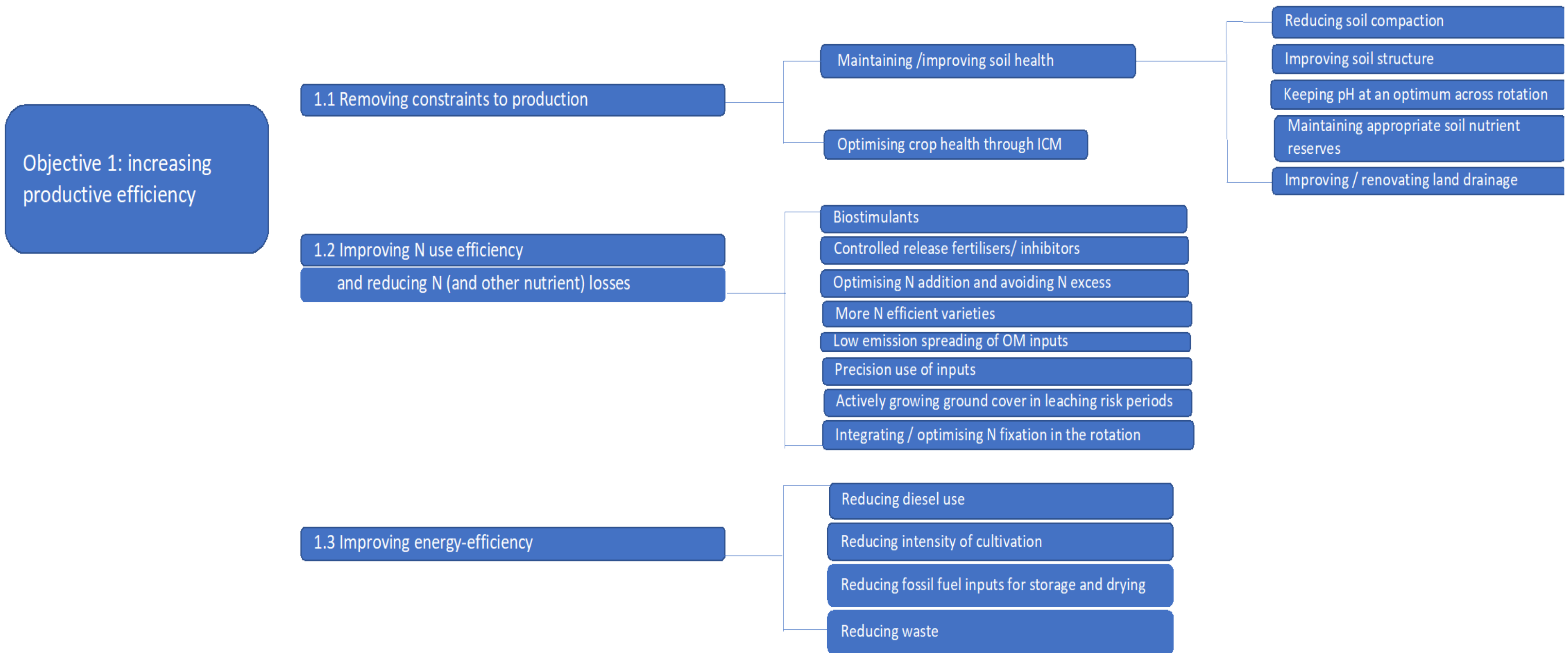


Figure 1 **Taxonomy of interventions that have been suggested as leading to reductions in net GHG emissions for combinable cropping systems.**

a) Objective 1: increasing productive efficiency

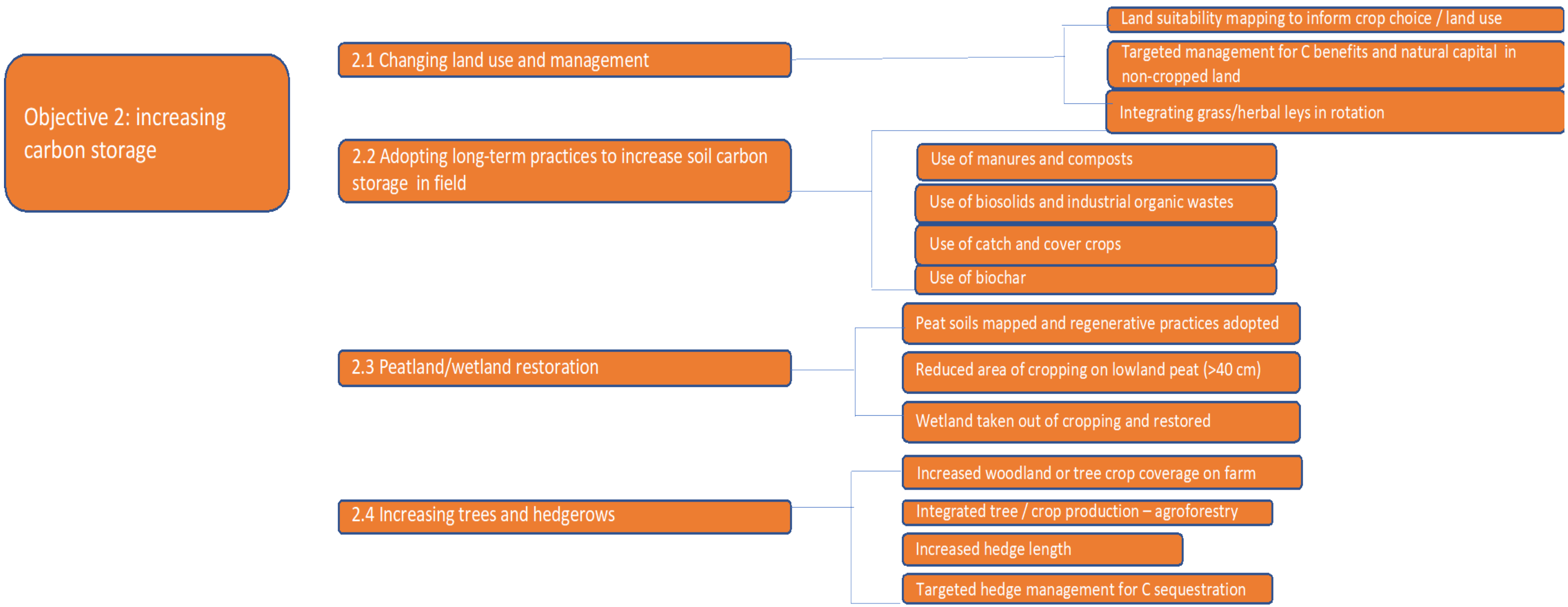


Figure 1 Taxonomy of interventions that have been suggested as leading to reductions in net GHG emissions for combinable cropping systems.
b) Objective 2: increasing carbon storage

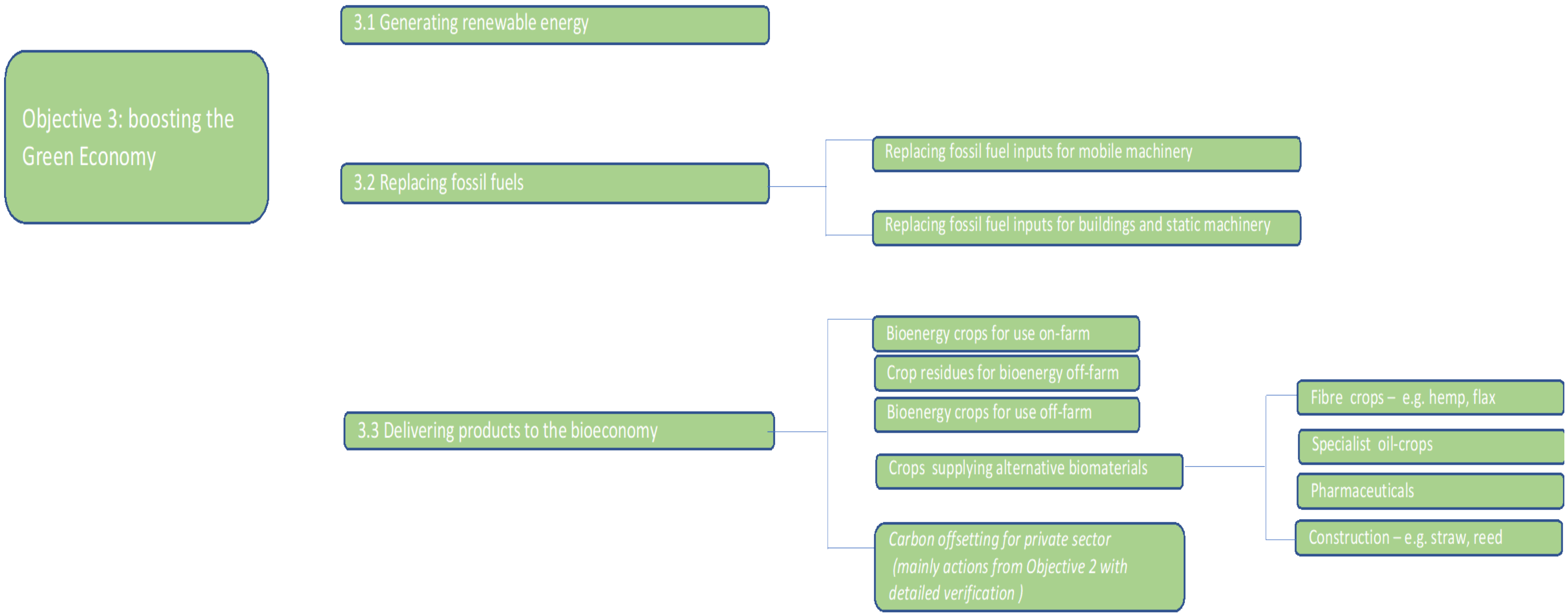


Figure 1 Taxonomy of interventions that have been suggested as leading to reductions in net GHG emissions for combinable cropping systems.
c) Objective 3: boosting the Green Economy

4.2. Who? Active and recent research in the UK

4.2.1. Methods

The scoping review first used the categorisation of research projects used within three key UK funding databases – UKRI Gateway to Research (GtR); Defra ScienceSearch and the EU research portal (cordis) to identify research relevant to the measurement or mitigation of greenhouse gas emissions in agriculture. In addition, simple search strings containing keywords derived from the name of the intervention (Figure 1) with truncations and synonyms and the phrase "greenhouse gas" were used to identify a further shortlist of projects for fuller review. The Natural England Access to Evidence database and the Environment Agency publications catalogue were also screened; neither were easy to search and did not contain records of on-going research projects. The summaries provided in the databases for the sub-set of projects identified in this way were screened for relevance to arable cropping systems in the UK and for currency; only projects beginning after 2005 were selected as, for the purpose of scoping, it was assumed that the findings of earlier projects will have been incorporated into the underpinning knowledge base. The focus was on providing links to projects and research teams thus revealing both:

- Key research expertise and associated research groups within the UK
- Possible agglomerations of research or review evidence that could be drawn on to develop EFI products and services that may not yet be published

Where relevant projects were identified, each was added to the master EFI Projects list, with the project number and reference databases identified, to provide quick access to direct project evidence associated with each pillar. For these key sources, the record also provides lead research organisation, project start and end dates and the lead researcher where given. The list includes research and research consultancy projects, not distinguished, and also studentships. From the research record within the database, it is often possible to access summary research findings, full research reports or links to publications. The EU H2020 project - Co-ordination of International Research Cooperation on soil CArbon Sequestration in Agriculture (CIRCASA) had recently undertaken stocktaking of research networks and projects working on greenhouse gas mitigation in agriculture, especially but not only those focused on increased carbon storage in soils. Hence we were able to use their report of the resulting draft network map (CIRCASA, D1.1), which was used to provide an initial list of leading research players working on greenhouse gas mitigation in arable systems outside the UK within similar cropping systems and climates.

These data were used to compile a draft research mapping diagram, which was circulated to key stakeholders (the GHGAP group and some of the key researchers identified in the first steps) for comment, for example the identification of missing research groups, projects etc. This was then updated as new contacts / projects were identified.

4.2.2. Results

Defra has funded 192 research projects in the area of agriculture and climate change since 1995. Since 2005, 7 of these were relevant to the impacts of interventions on GHG emissions on arable farms; further searching in the Sciencesearch database identified a further 5 relevant projects (e.g. evaluation of the impact of current agri-environment scheme options on soil carbon (project LM0468) or more widely on the value of agri-environment schemes for GHG mitigation (project LM0470). Defra often takes up to a year after project completion to approve final reports for publication, where they are available, they can be accessed via the Sciencesearch project record. Some current projects do not appear on Sciencesearch – for example, Defra has commissioned a project (SCF0120: Delivering clean growth through Sustainable Intensification) that is synthesising the evidence on the technical efficiency of a wide range of options to mitigate GHG emissions and then scrutinising the breadth of approaches for their feasibility for implementation on farm.

Defra made a large investment in research through the multi-actor co-ordinated GHG Platform between 2010 and 2017 to improve and develop the accuracy and resolution of the GHG reporting system for UK agriculture, across all sectors. The programme built upon previous research, combining field experimentation, modelling and scoping of data sources to fill knowledge gaps and provide new experimental evidence on the factors affecting emissions together with statistics relevant to changing farming practices in the UK. The programme also included the development of detailed case studies which explored the interactions and impacts arising from the adoption of mitigation methods at farm-scale (project AC0227) and provides comprehensive evaluation in practice for likely combinations of mitigation actions. Although this programme is complete, the research teams still regularly collaborate in providing evidence and analysis e.g. for the Committee on Climate Change and several of the research scientists have key roles within the IPCC Working Group on Mitigation of Climate Change.

Research projects funded via UKRI include both near-market, often industry-led, research (funded by Innovate) and strategic research focused on increasing understanding of underpinning mechanisms (funded by BBSRC, NERC, EPSRC and the other research councils). Since 2005, NERC have funded 28, BBSRC 19, EPSRC 9 and Innovate 4 relevant projects. The EU databases are more difficult to navigate; we identified 7 relevant research projects, but recognise that there will have been relevant projects funded in FP6 and 7, which will not have been identified by this route. The agricultural European Innovation Partnership (EIP-AGRI) funds short projects, workshops and focus groups to investigate issues and inform innovation. For example EIP-AGRI focus groups have brought together experts (including farmers, advisers, researchers, up- and downstream businesses and NGOs) to seek solutions and innovative approaches on topics such as: agroforestry; carbon storage in arable farming, fertiliser efficiency, renewable energy on the farm, soil organic matter (https://ec.europa.eu/eip/agriculture/en/focus-groups).

Much of the work completed in strategic research projects is reported through the peer-reviewed literature; the GtR database provides summaries of findings and links to published papers, where these have been updated by the research teams. The strategic research is, by its nature, less relevant to the immediate practical issues of on-farm mitigation but often is at the forefront of investigation into new approaches e.g. into the replacement of fossil fuels in static and mobile machinery, new more efficient fertiliser or precision application. The Economics and Social Research Council have also funded work on farmer decision-making; much of this was not directly relevant and hence is not summarised in the master EFI Projects list, but it provides theoretical underpinning to understand the role of farmer innovation and interaction with advisors during any land use/ management change such as will be needed to achieve Net Zero. For example, socio-economics is integrated into consideration of actions to maintain/ improve soil health within the EU project - Soil Care for profitable and sustainable crop production in Europe (id 677407).

Of particular relevance in the pilot/ development phase of EFI is the active NERC-funded research project - What are the impacts of agricultural soil and crop management on greenhouse gas fluxes? - Informing post Brexit agricultural subsidy policy (NE/S015949/1). This project will develop a systematic map of the evidence relating to the impact of soil and crop management of arable land in temperate regions on GHG flux, including both mineral and organic soils. Additionally, an interactive visualisations platform will be produced enable users to interact with the map and select specific areas to examine in more detail. The systematic map protocol has been published (Collins et al. 2019). However, the lead researcher is currently on maternity leave and the project is in abeyance until she returns; hence it has not been possible to liaise directly during this Scoping Review. The primary question defined for the systematic map is narrower than was used for this scoping review and the focus is on replicated observational and manipulative studies with measurements of the fluxes of greenhouse gases (methane, nitrous oxide, carbon dioxide). Hence the work will largely build forward from the work of the GHG Platform.

The UK research landscape underpinning the measurement or mitigation of greenhouse gas emissions in UK cropping systems is therefore widespread and diverse (Figure 2). The research teams identified here are often working in collaboration (in a range of configurations depending on the research question under investigation). The links between bio-economy research and practical agronomic application are the least well developed; in addition, much of the underpinning work on renewable energy and fossil fuel replacement is not directly targeted at the agriculture sector (which is likely to benefit from on-going research for construction and road haulage). However, there are relevant international collaborations in place including informal knowledge sharing via academic societies as well as through formal research collaborations.

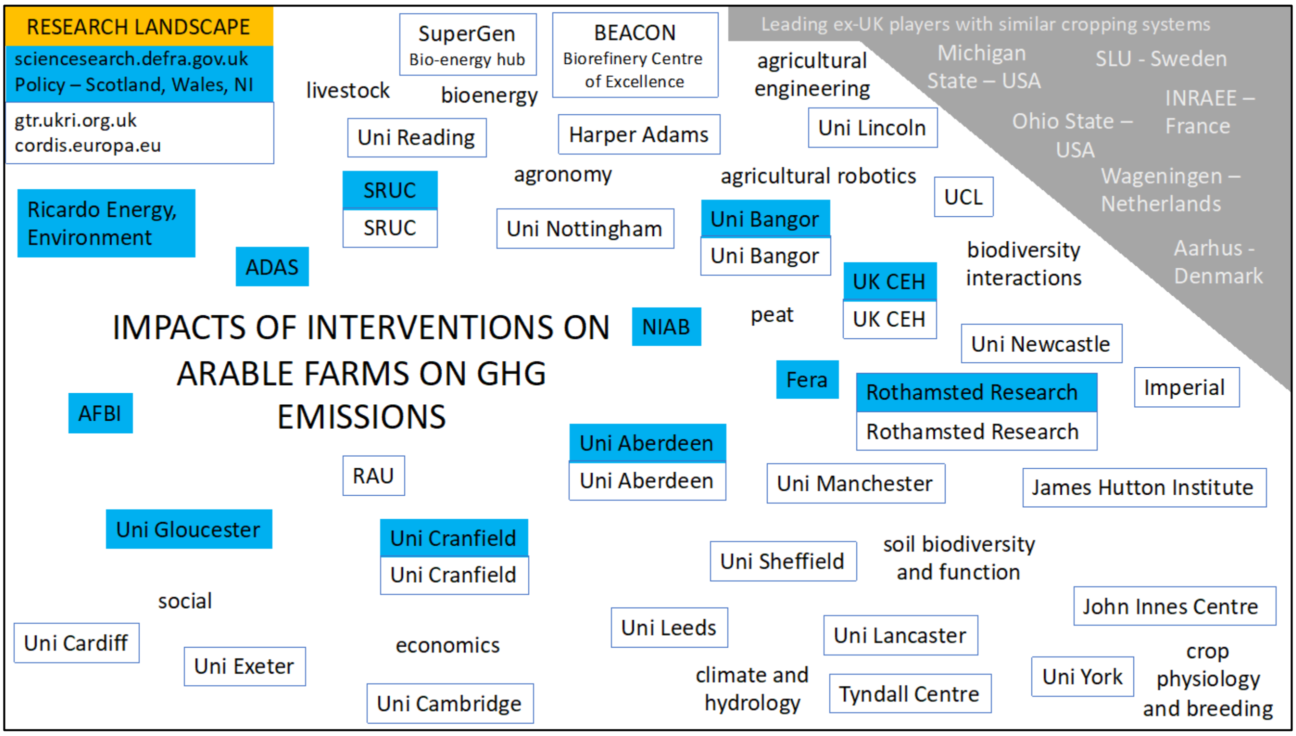


Figure 2 Outline diagram showing the main research organisations actively engaged in measurement or mitigation of greenhouse gas emissions in UK/temperate arable cropping. cropping. Policy-maker commissioned and other research projects are shown, together with the main research specialisms contributing to the breadth of underpinning research in this topic area.

4.3. What do we know? Systematic mapping of the published evidence

4.3.1. Methods

The scoping review worked from the principles of a systematic mapping exercise as outlined by James *et al.* (2016). This method was chosen as the most appropriate approach to minimise bias towards particular publication journals or authors and to ensure searches captured as many relevant publications as possible. However, in this scoping review, there was a focus on the identification of robust syntheses rather than primary research studies and their findings. We defined robust syntheses as peer-reviewed publications that report:

- Systematic review. These provide a critical assessment and evaluation of all research studies in order to answer a specific question with clearly defined inclusion criteria.
- Meta-analysis. These present the statistical analysis of a collection of data from individual primary studies for the purpose of integrating the findings. Primary studies are often, but not always, collated through a systematic review process.
- Descriptive reviews. These are old-fashioned literature reviews with some data synthesis, or integrative modelling. These are often important to draw out wider context that is not addressed in a tightly defined systematic review. Some descriptive reviews contain little

critical data synthesis and report the authors' reasoned opinions; however, these can usually only be distinguished once the full source considered in detail. Descriptive reviews may also include Evaluations in Practice which provide critical evaluation of on-farm experiments or practical implementation.

This focus was chosen as where systematic reviews and meta-analyses for a set of questions already exist, there is potential for a higher level of evidence synthesis, into summaries that describe results across a range of possible options. Ultimately EFI seeks to create these higher-level summaries and then then develop evidence-translation materials for farmers and their advisors hence this pilot focused on evaluating the potential for this higher level synthesis as the main priority.

Determination of search terms

The search strings were set up based on the following PICO with a range of truncations and synonyms (e.g. cultivation / tillage) building from the mitigation interventions already identified (Figure 1).

Population	In temperate combinable cropping systems
Intervention	does xx e.g. Reducing intensity of cultivation
Comparator	(in comparison with conventional cropping without xx)
Outcome	deliver Improved productive efficiency, and/ or Increased C storage, and/ or Outputs to the green economy and thereby reduce net GHG (per unit produce/ per unit area)

Search and screening approach

The searches took place initially in Scopus and thereafter searches were repeated in other knowledge repositories: Researchgate, GoogleScholar. More bibliographic databases could have been used as they give a slightly different coverage, but the aim of the scoping review was to establish the information density for the interventions and the time expended in searching beyond these three repositories was not worthwhile for the number of newly identified resources. The search strings used contained the keywords in the name of the intervention (with truncations) and synonyms and the phrase "greenhouse gas".

Where a list of resources (>50) was identified the list was reviewed by paper category to establish how many of the resources fell into the "Review" category. This has a slightly different definition in different databases but in all cases this classification contains all the robust synthesis types identified above. If there were more than 10 "reviews" identified, the resource list was restricted to that category and the abstracts were read to screen the papers for relevance to the Population. The existence of a body of high-quality evidence in robust syntheses, addressing all aspects of the net GHG emissions associated with an intervention, is considered to provide sufficient evidence from which to begin to draw out narrative summaries to review the impact of the interventions and underpin EFI in its pilot stage. This level of evidence maps to the highest levels of the draft EFI 'strength of evidence' categories (Levels 5 and 4).

Where there were <10 reviews, the reviews were screened first but if fewer than 5 were relevant, then the full resource list was first limited using the additional search term "crop" and then also "temperate / UK" and then the abstracts of this limited list were screened. This approach allowed rapid identification of:

- interventions for where there is a sufficient evidence to draw some conclusions about the impact of an intervention on the net GHG, or detailed evidence on some aspects but an incomplete evidence base (Level 3).
- interventions where the body of evidence is incomplete or has significant short-comings, e.g. reviews based on little robust experimental data, so that conclusions about the impact of the intervention are difficult (Levels 2 and 1).

This screening approach is designed to be more likely to over-value weaker evidence sources in the initial screening, to increase the likelihood that interventions will be considered for fuller rating within EFI. Hence where more detailed reviews are then conducted, the overall strength of evidence weighting may change from that allocated during scoping.

In addition, policy and researcher stakeholders (as identified above) were asked for recommendations of key synthesis documents, including policy and practice guidance documents. Such guidance documents are often (but not always) developed following expert review and synthesis of evidence – hence where relevant policy and industry guidance is identified, we also used the snowballing technique from the reference lists and footnotes to identify the supporting evidence syntheses. The strength of this approach is that it is multi-disciplinary and recognises the importance to decision-support of evidence collected and published in different ways whilst at the same time providing a clear framework of analysis.

Key relevant sources for each intervention were recorded in the master References list (with their DOI or in some cases a web address, URL) to provide quick access to the key evidence sources associated with each pillar. For these key sources, the record also provides first author, date of publication and the nature of the source specifically highlighting systematic reviews. Open access publications are also identified clearly.

4.3.2. Results

Smith et al. (2008) provided the first estimates of agricultural GHG mitigation potential, including all GHGs, and presented a quantitative comparison of the benefits of different interventions by bringing together datasets from across the world with breakdowns for all global regions and all gases; their reference list contains 194 key studies on GHG emissions available in 2008. The mitigation options reviewed used current technologies and were considered to be able to be implemented immediately. The majority of interventions considered here (Figure 1) were included in the assessment of Smith et al. (2008). They identified interventions with high potential for GHG mitigation in croplands as agronomic practices increasing yield and/ or crop residue returns, improved N use efficiency, reduced tillage intensity, and optimisation of water balance (irrigation/drainage). Land-use/ systems change with reversion of arable cropland to grassland or woodland was identified as one of the most effective options to reduce net GHG whether in whole or part-fields (e.g. field margins, shelter-belts, agro-forestry); however, it was also noted that given the impacts of such reversion on agricultural productivity, it should only take place on land of marginal productivity. Smith et al. (2008) has not been supplanted as the key reference source to provide an integrated assessment of GHG mitigation interventions for agriculture with over 1250 citations in peer-reviewed papers and over 100 citations per year since 2012.

MacLeod et al. (2015) developed the economic aspects of analysis of GHG mitigation and reviewed 65 current international studies of the cost-effectiveness of eight categories of agricultural mitigation measures, covering 181 individual interventions. The analysis summarised knowledge about the range of feasible agricultural mitigation options, whether they can be technically effective, economically efficient, and socially acceptable by deriving marginal abatement cost curves. No meta-analysis was completed; the average cost-effectiveness of measures was considered to be less useful than showing the variation between countries and studies, in part due to contextual differences. Macleod et al. (2015) illustrated these differences in nine case studies, generally using a cost-engineering approach.

Three subsequent descriptive reviews have been identified in this scoping review which have covered the same breadth (but without repeating the depth of analysis presented by Smith et al. 2008 or Macleod et al. 2015) and which have further developed the analysis to address issues associated with the design of farming systems to meet the challenges of GHG mitigation and climate change adaptation (Paustian et al. 2016; Debaeke et al. 2017). Rial-Lovera et al. (2017) provide a focused review of the same issues for UK cropping systems.

Some other key reviews have focused on the technical potential and feasibility of delivering reductions in GHG by comparing/ integrating impacts for several interventions:

- Snyder et al. (2009) present a descriptive review of the effects of inorganic fertiliser N source, rate, timing, and placement, in combination with other cropping and tillage practices, on GHG emissions to identify best-management practices for the use of fertiliser (considering interventions from within Objective 1.2)
- Rees et al. (2013) present a systematic review of the impacts of possible mitigation options for N_2O emissions in the UK, also investigating and identifying driving factors (largely reviewing interventions from within Objective 1.2); this publication directly results from the work of the GHG Platform described above.
- Dignac et al. (2017) provide a meta-analysis of the impact of a range of management practices on soil C storage for managed ecosystems in France together with a critical summary of current knowledge of the mechanisms (largely reviewing interventions from within Objectives 2.1 and 2.2)
- Minx et al. (2018) present a systematic review (as part of series of papers) to assess the economic and biophysical limits associated with a range of negative emissions technologies together with the challenges associated with implementation (including review of interventions within Objective 2 and 3.3)
- Sykes et al. (2020) present a structured review of a range of interventions that can deliver increased soil C storage and then assess the barriers and potential incentives towards practical implementation (including interventions increasing productivity within Objective 1, and within Objective 2)
- Diakosavvas and Frezal (2019) present a review of the opportunities and policy challenges for agriculture's role in the wider bioeconomy (including some discussion of the role of interventions within Objective 3.3 in displacing fossil fuel emissions)

A broad overview of the evidence base available for each intervention (considered individually) that have been suggested as leading to reductions in net GHG emissions for combinable cropping systems is given in Table 1 over the following pages. Key relevant sources identified for each intervention are given in the master References list.

Table 1: Overview of the evidence base available for each intervention (considered individually) suggested as leading to reductions in net GHG emissions for combinable cropping systems. Where SR = systematic review; DR = descriptive review

a) Objective 1: increasing productive efficiency

		Notes
1.1 Removing constraints to production	Maintaining / improving soil health	Often assumed, some single factors studied but components complex and interacting; research on crop heath often focused on crop quality/ productivity
	Optimising crop health through ICM	
1.2 Improving N use efficiency and reducing N (and other nutrient losses) *Syntheses at farm-scale highlights the relative importance of 1.2 – more product per unit N; or simply less fertiliser N overall with the same food production*	Biostimulants	SR and >4 DR available
	Controlled release fertilisers / inhibitors	>4 SR available
	Optimising N addition and avoiding N excess	3 SR, >4 DR and modelling studies available
	More N efficient varieties	>4 DR and modelling studies available
	Low emission spreading of organic material inputs	Mainly information from livestock-based systems; best reviewed in context of scoping for dairy systems
	Precision use of inputs	1 DR linked to precision N use
	Actively growing ground cover in leaching risk periods	3 SR, >4 DR = Use of catch and cover crops
	Integrating /optimising N fixation in the rotation	SR and >4 DR available
1.3 Improving energy efficiency	Reducing intensity of cultivation	>4 SR available
	Reducing diesel use	Taken as read; to deliver reductions in practice is complex and interacting. Some case studies available.
	Reducing fossil fuel inputs for storage and drying	
	Reducing waste	

Table 1: Overview of the evidence base available for each intervention (considered individually)
Where SR = systematic review; DR = descriptive review; LCA = life-cycle analysis
b) Objective 2: increasing carbon storage

		Notes
2.1 Changing land use and management	Land suitability mapping to inform crop choice /land use	Mentioned in several DR
	Targeted management for C benefits and natural capital in non-cropped land	Management interventions mainly drawn from 2.3 and 2.4
	Integrating grass/herbal leys in rotations	DR available; also often covered by SR and DR addressing 2.2
2.2 Adopting long-term practices to increase soil carbon storage in the field *> 4 SR addressing soil C storage / sequestration measures and implementation in combination*	Use of manures and composts	>3 SR and DR available – with OM source comparisons including some industrial wastes
	Use of biosolids and industrial organic wastes	Broad LCA based approaches needed together with on-farm impacts – link to bioeconomy; SR available for whole chain
	Use of biochar	4 SR/ DR; LCA based approaches needed – link to bioenergy
	Use of catch and cover crops	3 SR, >4 DR = Actively growing ground cover
2.3 Peatland /wetland restoration *Site-specific environmental and socio-economic issues recognised to dominate potential for changes in practice*	Peat soils mapped and regenerative practices adopted	2 SR and DR on C stock changes also often covered by reviews addressing land-use change
	Reduced area of cropping on lowland peat	
	Wetland taken out of cropping and restored	
2.4 Increasing trees and hedgerows	Increased woodland or tree crop coverage on farm	>2 DR available Arable (non-profitable) soils seen as key target; also often covered by reviews addressing land-use change
	Integrated tree/ crop production - agroforestry	SR and >2DR available; wide range of potential systems
	Increase hedge length	Research project; UK-based DR available
	Targeted hedge management for C sequestration	

Table 1: Overview of the evidence base available for each intervention (considered individually). Where DR = descriptive review

c) Objective 3: boosting the green economy

		Notes
3.1 Generating renewable energy		Not cropping or agriculture specific; relevant research projects. On-farm case studies available.
3.2 Replacing fossil fuels	Replacing fossil fuel inputs for mobile machinery	DR available; most information not agriculture-focused, learning from haulage and construction sector. Innovate applied research projects.
	Replacing fossil fuel inputs for buildings and static machinery	Most information not agriculture-focused, learning from construction sector.
3.3 Delivering products to the bioeconomy	Bioenergy crops for use on-farm	DR available for maize, some relevant research projects.
	Crop residues for bioenergy off-farm	DR available focusing on life-cycle issues, some relevant research projects. Non-cropping alternatives – hence food for fuel (or equivalent) issues need to be tackled. Socio-economic assessment needed alongside technical
	Bioenergy crops for use off-farm	
	Crops supplying alternative biomaterials	
	Carbon offsetting for private sector (mainly actions from Objective 2 with detailed verification)	DR available, focused on operation and verification issues

Interventions with a body of high quality reviews linking the intervention to net GHG

For several interventions, there were a number of specific systematic reviews bringing together evidence, focusing on one main aspect relating to net GHG, commonly either impacts on N_2O emissions or soil C storage. These reviews sometimes also provided synthesis or modelled estimates of indirect impacts such as displacement of fossil fuel use, or reduced off-site N_2O emissions where leaching of nitrate was reduced. In some cases the reviews, also provided synthesis of evidence for impacts on other aspects e.g. crop yield, other environmental impacts. It is important to note that systematic evidence synthesis is a relatively new process and tends to have been applied where the interventions are new or where there has been some dispute/ uncertainty about their impact. For seven interventions, it was considered that there was an extensive body of high-quality evidence reviews that would allow strong conclusions about impacts on net GHG to be drawn:

- Controlled release fertiliser/ inhibitors
- Optimising N addition and avoiding N excess
- Use of manures and composts
- Use of biosolids and industrial wastes
- Reducing intensity of cultivation
- Actively growing ground cover in leaching risk periods + Use of catch and cover crops (considered together)
- Use of biochar

Interventions with at least one high-quality review and a range of other high-quality evidence

For other interventions, whilst there was a underpinning body of evidence, it was not so strongly founded on robust syntheses. For biostimulants, there was relatively little published UK-relevant field evidence and the reviews available often described the potential impacts on productivity or N use efficiency with links to measured impacts on plant physiology under controlled conditions. There are also a wide range of “modes of action” identified and hence grouping of all these products together as biostimulants makes the evidence base harder to assess.

For other interventions, the underlying principles were well established e.g. C storage in trees, change in GHG balance in drained vs undrained wetlands, but detailed synthesis of evidence directly relevant to the application of the intervention in UK cropping systems was either not available or covered only part of the GHG balance. For six interventions, it was considered that there was at least one high-quality evidence review and a wider body of evidence that could allow some conclusions about the impacts on net GHG to be drawn:

- Biostimulants
- Integrating/ optimising N fixation in the rotation

- Integrating grass/ herbal leys in rotations
- Peatland/ wetland restoration
- Increasing trees and hedgerows
- Integrated tree/ crop production – agroforestry

Interventions where the body of evidence linking interventions to net GHG is limited

For some interventions, there is no strong body of evidence linking the intervention to GHG emissions, partly because the impact of the intervention is considered clear e.g. interventions that generate renewable energy directly, or those that reduce or replace fossil fuel use in mobile machinery (and buildings and static machinery). However, there is still a need for rounded evidence to allow actions that deliver these objectives to be compared with one another and for the costs and benefits of these options to be assessed at farm-level. For hedge management, there is one comprehensive UK-based study (Axe et al. 2017) but no wider body of evidence to consider alongside this. In other cases, the evidence in principle is sound and described in reviews (e.g. using More N efficient varieties) but this is still at discovery and development stage with little evidence of testing under field conditions relevant to UK cropping.

Interventions that address constraints to production or inform crop choice/ land use are identified in several of the overall reviews when the overall need to improve productive efficiency is highlighted and hence it is assumed (and occasionally stated) that actions which remove constraints and allow crops to achieve their yield potential more closely in that growing season will support reductions in net GHG. However, although there are research studies (and some syntheses) that address links between crop health and productivity/ crop quality, the impact of these management interventions is very rarely directly associated with, or quantified in terms of, net GHG. Studies and syntheses referring to soil health in cropping systems often include interventions such as reduced tillage intensity or use of catch and cover crops that are covered separately in this taxonomy. In some cases, reviews of management changes e.g. adoption of controlled traffic (Antille et al. 2015) show impact of the practice on some soil properties (e.g. soil structure) and then provide clear reasoning of the wider impact on net GHG but without a depth of direct evidence. The impacts of removing constraints to production is therefore often taken as read, although in practice the impacts between aspects of crop and soil management on net GHG are likely to be complex and interacting.

There is an overall lack of evidence in relation to interventions that are grouped in Objective 3 - Boosting the green economy. As discussed above, this is partly because links between bio-economy research and practical agronomic application are relatively weakly developed; in addition, interventions that displace the need for fossil fuel are often perceived positively, however there is a need for a full inter-disciplinary consideration of whole life-cycle issues, whether GHG or economics; it is important that the land use questions arising from displacement of food for fuel (or equivalent) issues are tackled. Hence, socio-economic evaluation is needed alongside technical assessments.

4.4. How do we know if things are changing? Key performance indicators, models and benchmarks

4.4.1. Methods

Any final set of indicators for EFI are likely to include indicators of both intermediate (knowing about EFI, accessing the evidence, using the evidence to inform decision-making) and ultimate outcomes (e.g. reduced GHG emissions, increased productivity with the same resource inputs, increased soil/ biomass carbon storage). Therefore, an additional focused aspect of the review process was a review of potential key farm performance indicators and associated benchmarks that allow the effectiveness of policies and practices for GHG mitigation in arable farming to be evaluated with an appropriate balance of simplicity, practical relevance, comparability, cost (including data collection time), accuracy and precision. EFI is also proposing to provide opportunities for farms to robustly estimate emissions (and carbon storage) for their individual situation, together with associated benchmarks that can help farmers decide where to focus in order to address their Net Zero opportunities.

If GHG emissions were able to be routinely measured, or estimated from proxies, then this would provide direct indicators and the use of scientifically-defined thresholds in rules and regulations would appear to be simple in principle as described by Bouma (2011): (1) define the problem; (2) assign an appropriate state indicator for the problem being distinguished; (3) define a threshold value for the state indicator; (4) measure the value of the state indicator in the problem area being studied; (5) compare measurements with the threshold, and (6) conclude that there is no problem when the measured values are below the threshold or conclude that there is a problem when this is not so; (7) address the problem if it occurs. Unfortunately, as Bouma (2011) discusses, major complications make this logical and simple approach often unfeasible for environmental indicators. Direct measurement of GHG emissions is not simple or cheap and hence is not a practically relevant option for evaluation of the impacts of management changes on farm; continuous measurements are required ideally, and these need costly and time-intensive automated chambers or flux towers (Denmead, 2008). However, targeted measurement of GHG emissions, within carefully designed research projects and monitoring networks, will continue to be required to address questions about the factors driving emissions, evaluate interactions and feedbacks in practice and inform the development of inventories and models for use at national or farm-scale (Ogle et al., 2020). Hence, the indicators of GHG fluxes used to underpin policy and practice need to be based on proxy values that are easier to obtain and control and are assumed to characterise the total GHG flux, soil C storage etc. This assumes a well-defined relationship between the true indicator and its proxy – and this is also not simple for environmental indicators (Bouma, 2011) . GHG emissions also vary both spatially and temporally and hence the definition of system boundaries in space and time is a critical part of the definition of key farm performance indicators and are these likely to vary between arable and livestock (including mixed) systems (see Hutchings et al. 2020 who discuss this issue for N balances). A range of indicator types have been proposed with varying complexity and data requirements (Figure 3); many are also in use in practice. Here we have focused on indicators that can be used only to evaluate the effectiveness of policies and practices for GHG mitigation in arable farming.

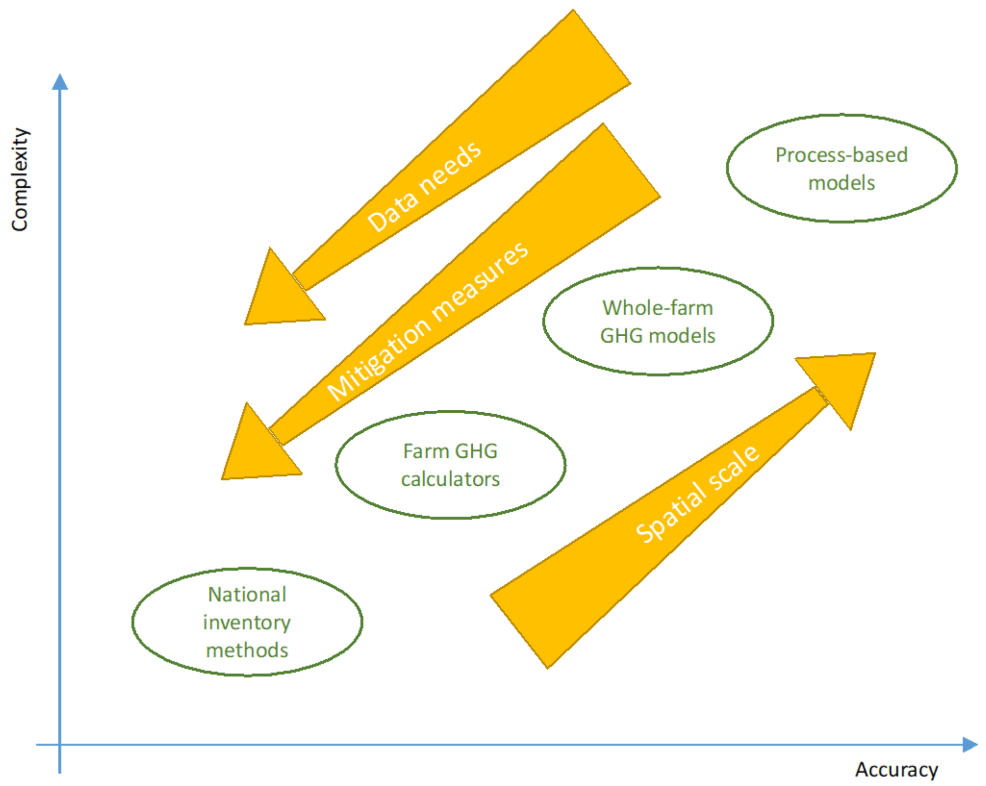


Figure 3. Indicative mapping of approaches to the estimation of GHG emissions. The simplest approaches such as the Tier 1 National Inventory methods require relatively little data but as a consequence are unable to easily account for the impact of mitigation methods taking places within farming systems. To be able to account for these impacts, more complex approaches with higher data requirements are required. Improvements in accuracy may depend on the quality of the data available and the validation of models for the specific system/ environment.

Some sources referring to the development of measurements and indicators of greenhouse gas emissions at farm-scale were identified during the main literature search phase associated with the interventions (described in 4.3.1). Stakeholder recommendations arising from the same process also highlighted the key UK government sources. Additional searches were carried out in Scopus and Google using the terms "greenhouse gas" and indicator and farm. Relatively few relevant sources were identified in the peer reviewed literature, but a range of policy and practice guidance was identified for review.

The UN Environment Programme (2019, 6th Global Environmental Outlook) outlines how both top-down case-based evaluation and bottom-up indicator-based assessments can be combined to increase the effectiveness in evaluation of environmental interventions. Therefore, we report briefly on approaches to GHG emissions indicators at national-scale within the UK, together with a more detailed review of approaches that have been developed or proposed at farm-scale to provide data to identify opportunities for mitigation and allow farm-level monitoring of progress towards net zero GHG. If a measure is to function as a useful indicator at either scale, it must change year on year in a way which reflects the evolving GHG balance. To provide a robust framework, indicators should be interpretable in relation to other productivity and environmental indicators and easy to compare with equivalent data from other times or places. Different data types from which indicators can be derived are likely to be available at farm than national-scale – however, awareness of the relevant national-scale indicators and how they are calculated provides useful context to the consideration of farm-scale indicators.

4.4.2. Results

National-scale – GHG emissions, indicators

Currently at national scale, GHG inventories submitted under the United Nations Framework Convention on Climate Change provide the basis for monitoring emissions and assessing progress in reducing emissions via mitigation programmes. The Intergovernmental Panel on Climate Change (IPCC) has developed inventory guidelines for monitoring national emissions that allow accurate estimates to be made at national scale that are as precise as is feasible (IPCC, 2019). Improving inventories is largely predicated on developing country-specific emission factors (categorised as Tier 2 methods by the IPCC) or model-based approaches for deriving dynamic emission factors both spatially and temporally (categorised as Tier 3 methods by IPCC), as well as improving data collection on the activities taking place at farm level that drive emissions and/ or their mitigation. Policy commitments are set relative to emissions in a reference year (1990 is used as reference in the UK), and so improvements from mitigation actions must be tracked over time to show continued uptake and progress and, where appropriate, to justify reductions in emissions factors.

As identified above, Defra funded extensive research activity, though the seven-year multi-collaborator programme of the Agriculture GHG research Platform, to improve and develop the accuracy and resolution of the UK reporting system by providing new experimental evidence on the factors affecting emissions and statistics relevant to changing farming practices in the UK. This generated evidence for a UK specific method of calculating methane and nitrous oxide emissions that can better reflect the adoption of mitigation practices by the industry, enabling the forecasting and monitoring of performance against target emissions reductions. The Smart Agriculture Inventory was therefore adopted in 2018 (CCC, 2018) The UK provides an annual UK Greenhouse Gas Inventory report for submission which includes updates on the trends in GHG emissions by sectors including agriculture and land use, land-use change and forestry (e.g. BEIS, 2020).

Defra annually brings together existing statistics on agriculture in order to help inform the understanding of the link between agricultural practices and GHG emissions (e.g. Defra, 2019). Similar analysis also takes place in the Devolved Administrations. An indicator framework was developed in 2012 which allows consideration of agricultural emissions by sector with 10 key indicators, 5 of which provide indicators for livestock sectors. Data is collated from a number of sources to quantify the indicators, which are usually presented as time series from 1990; Table 2 shows the key indicators that are relevant for arable cropping and the main associated data sources. The associated report provides further context and commentary as well as breaking the data down further to consider N application and efficiency (yield per unit fertiliser N applied) by crop type. Defra (2019) also highlights newly commissioned research examining mitigation options for peat management in lowland peat under arable and horticultural cultivation. In addition, the Farm Accountancy Data Network (FADN) was launched in 1965, following EU Council Regulation 79/65, to provide business information on European agricultural holdings and assess the effects of the Common Agricultural Policy. In England and Wales, FADN data is collected through the Farm Business Survey (FBS) and these data are also used to provide context and some of the further depth in analysis alongside the key indicators. The FBS data are collected at the individual farm level (circa 2300 farms every year) covering a representative sample of farm types and sizes, and then are analysed, anonymised and aggregated (at a range of levels) to give an excellent summary resource, primarily of accountancy records, but some physical information and details of farm structure are also available.

Table 2 Leading indicators from the Defra 'Greenhouse gas emissions for agriculture' framework that are relevant in combinable cropping systems together with the main data sources from which they are estimated; for more detail see Defra (2019)

Defra key indicator	Main data sources used
1 Attitude and knowledge	Defra Farm Practices Survey
2 Uptake of mitigation methods	Defra Farm Practices Survey - some assumptions on uptake and relatively few of the mitigation methods from Figure 1 included directly). Mitigation impacts modelled with Farmscoper.
3 Soil nitrogen balance	Methodology developed by OECD and adopted by Eurostat (2018). Data from Defra June Survey of Agriculture, the Cereal production survey and British Survey of Fertiliser Practice. Coefficients (e.g. N offtake in a tonne of wheat) regularly checked and updated,
8 Cereals and other crops - manufactured fertiliser application	British Survey of Fertiliser Practice data; Defra June Agricultural survey (for crop area data)
10 Organic fertiliser application	British Survey of Fertiliser Practice data

These indicators do not currently include any assessment of net change in soil carbon storage as a result of agricultural practice. Defra (2019) noted that research and monitoring is currently focussing on emissions from peat soils as this is the major uncertainty within this category.
Both the BEIS Agricultural Inventory work and Defra's more detailed analysis of agricultural emissions, use expanded data collection in existing survey schemes (e.g. through adaptation of the Farm Practices survey), modelling of indicators using already available data (e.g. in the Soil nitrogen balance), with additional surveys/measures for certain sectors or farms of interest (e.g. the research to underpin monitoring in lowland peat). These indicator frameworks combine approaches from within the indicator typology (Figure 3) to achieve GHG emissions indicators for agriculture at national scale that are as precise as is feasible Lynch *et al.* (2019) report many of the complexities of putting detailed agricultural sustainability indicators into practice in the Irish context, and therefore discuss many of the underpinning issues which BEIS and Defra tackled in developing these frameworks.

Farm-scale – net GHG emissions indicators

Any assessment of GHG emissions and the impacts of mitigation measures at farm-scale requires the collation of information and derivation of indicators for a number of components within the farming system. Even where livestock enterprises are disregarded, different indicator sets will be needed for non-cropped land and the land under crop production, where GHG emissions and mitigation for drained cropped peat soils under cultivation should also be estimated separately. The Defra key indicators can be applied at farm-scale with the information sources now directly taken from farm records, coupled to coefficients or models verified at farm-scale. However, a broader range of indicators are likely to be required to inform farm management practice and/ or provide verification of the impact of mitigation steps taken. As for national-scale reporting, it is likely that a range of approaches from within the indicator typology (Figure 3) will be required.

Where the focus is on improving productive efficiency, then at a whole-farm level, input/ output records collated over several years, should allow the impact of mitigation measures to be detected. For some farms, such data may be able to be resolved to field or management zone level without the need for any additional data collection. The impact on GHG emissions of the adoption of one or more mitigation measures, such as removing constraints to production from pests/ diseases, improved targeting of fertiliser or adoption of more N efficient varieties, should be revealed through reduction in total N fertiliser applications, or more output per unit of fertiliser applied, without the need for extra data collection (Figure 4). A similar approach would also allow the impacts of measures taken to improve energy efficiency to be considered, also without the need for additional on-farm data collection.

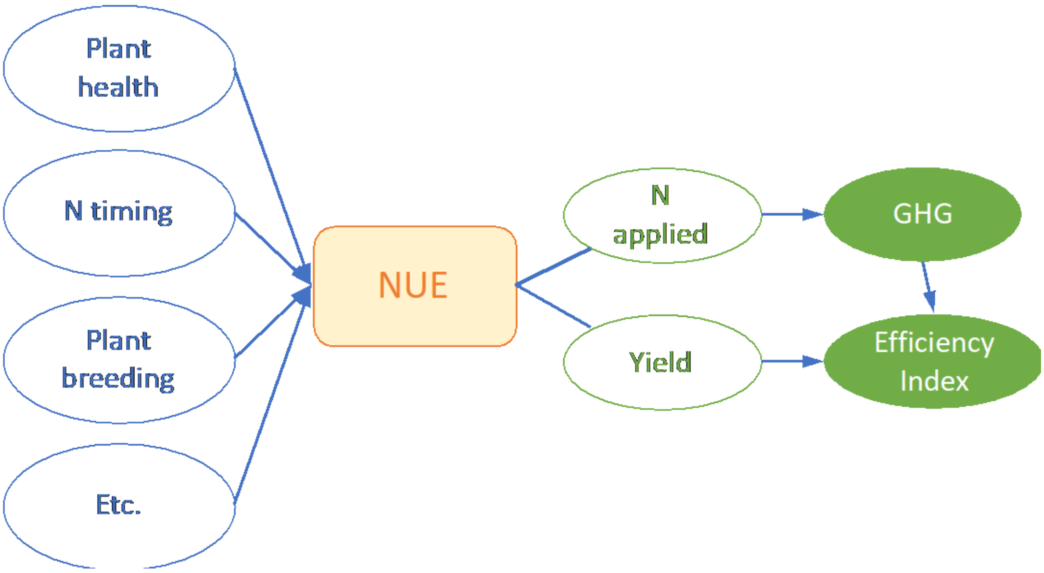


Figure 4 **Many management interventions may contribute to changes in nitrogen use efficiency (NUE) on farm. However, specific detail of these measures in terms of when/where or how they are adopted is not required to measure their net impact on GHG emissions, as the pathway to impact is a direct result of changes in either the amount of N applied or productivity.**

In other instances, data recording of the mitigation activity (what, when, how) will be needed to estimate the net impacts on GHG emissions. For example, for cover crops, where impacts on net GHG emissions arise mainly through changes in C storage or as a result of reduced N losses from the system (and hence off-site emissions); Figure 5. These cannot be easily measured directly and hence they would usually be estimated from empirical or process-based models.

On-farm measurement of soil organic carbon (SOC) is possible but requires careful collection of volumetric soil samples so that stone/ gravel content, organic C concentration of the fine earth (<2mm fraction) and soil bulk density can all be quantified to a known depth (Smith et al. 2019). A minimum of 30cm depth is recommended by the IPCC; deeper soil sampling (to 1m) is recommended if possible. To reduce potential errors and to ensure that small differences between C stock measures can be distinguished robustly, focused repeat-point sampling and/ or a large number of samples is often required. Sampling at 5 year intervals will also make the detection of the expected small changes more likely. For livestock production systems, FAO has published guidance on measuring and modelling soil carbon stocks and stock changes (FAO, 2019). To underpin understanding of change at farm-scale, a combination of direct measurements at defined monitoring sites with modelling is most likely to provide understanding of the impacts of management and across different soil types or different cultivation/ cropping systems. This approach is relatively costly and so would need to be accounted for within the monitoring and verification needed for any carbon offsetting projects (Smith et al. 2019). Similar challenges exist for the quantification of above-ground C storage in woodland/ hedgerows.

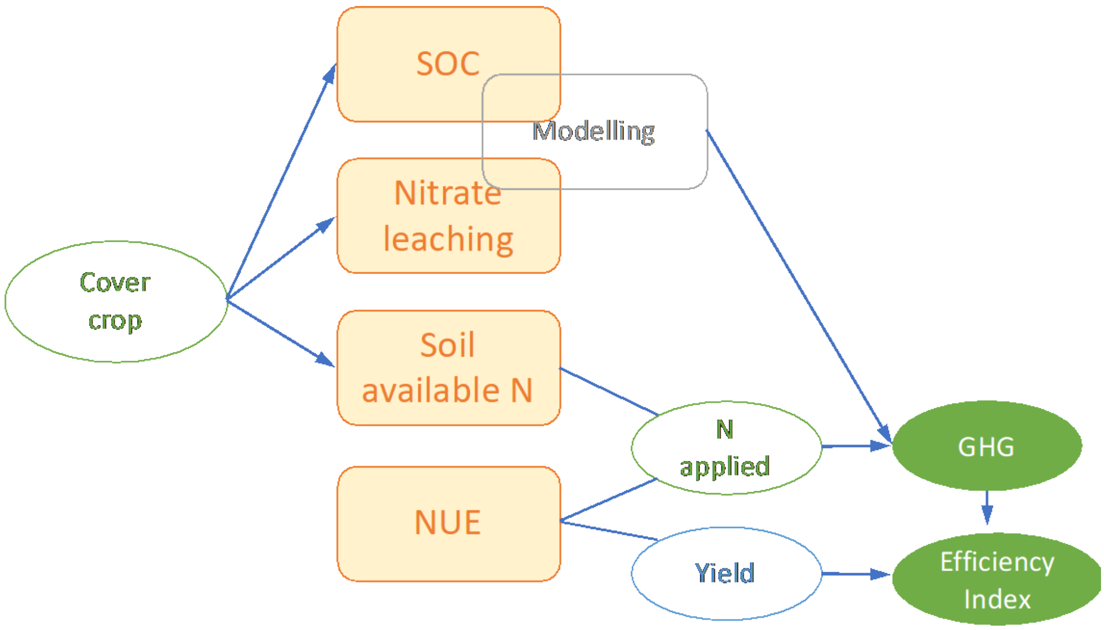


Figure 5 **Cover cropping may affect N fertiliser applications. However, the main impacts on net GHG result from impacts on soil carbon storage and nitrate leaching. Hence specific data of which cover crops are used, together with when and where are required to robustly estimate the net impact on GHG emissions.**

Individual farm-scale benchmarking of productivity in light of economic criteria is increasingly common. FBS provide a tool that allows individual farmers to enter their own data and hence compare themselves to the collated sector/ enterprise data; AHDB support on-farm benchmarking using FarmBench which is also designed to facilitate farmer discussion to understand site-specific differences and guide/ improve practice where appropriate. Hence it is not surprising that there are tools to support GHG emissions benchmarking (also known as C footprinting) in UK farming systems; 3 are readily available (Table 3). All of these tools are currently stand-alone and hence need data to be collated from other farm records (e.g. accounts and supplier invoices, crop-recording software, Basic Payment Scheme records) which can be time-consuming. The main data types needed for arable farms are:

- Annual fuel use by type
- Utility bills
- Assets (buildings, machinery, materials)
- Land area (soil type)
- Crop yields
- Fertiliser (manufactured and organic; type, rate)
- Agrochemical use
- Perennial biomass features (e.g. hedges, woodland)

Table 3: Easily accessible GHG emissions estimation/ benchmarking tools for use on-farm by farmers/ advisors in the UK

	CoolFarmTool	**Agrecalc**	**Farm Carbon Calculator**
Accessed via:	https://coolfarmtool.org/coolfarmtool	https://app.agrecalc.com	https://calculator.farmcarbontoolkit.org.uk
Designed initially for:	Supply chain by academics	Farm QA scheme (Scottish Beef Efficiency Scheme) by agri-consultants with academics	Farmers by farmers adopting renewable energy and consultants
Presents results:	By product	Whole-farm with breakdown by enterprise and product	Whole-farm
Key strengths	Simple initial data entry that can then be refined Quick overviews Globally applicable – other calculators for water, biodiversity …	Handles livestock systems most comprehensively Includes indicators for productivity Provides benchmarks to other farms	In depth approach to carbon sequestration Accounts for renewable energy and capital items Easy to see how changes affect the emissions
Weaknesses identified by farmer testers	Limited depth of consideration for livestock Hard to get whole farm overview	Needs some work to complete – comprehensive data requirements Not yet including impacts on soil carbon	Needs some specific information e.g. soil organic matter, soil bulk density Not yet fully recording livestock productivity

There are commonalities in the estimation approaches used by GHG emissions benchmarking tools, but the modelling differences between the tools mean that estimates made on a farm by one should not be directly compared with estimates made on another farm by a different tool. Currently these differences are much larger in livestock systems. Differences may also relate to the practicality of data collection e.g. fertiliser purchase (rather than use) records may be easier to access but may result in lower accuracy of the GHG estimates for the year. Care is needed to ensure that simplifications don't reduce the quality of the data for farm-level decision making. Despite the additional complexity, site-specific detail can allow targeting of mitigation actions (e.g. woodland creation) using data showing in-field variation in soil and/ or gross margin or significantly reduce implementation costs. As discussed for cover crops, data on where/ when mitigation is implemented may be required to generate indicators, but it can also be used to assess the factors affecting success, and to allow on-farm learning to support further adoption. It seems likely that the greatest benefits could accrue in the short-term by enabling data sharing between farm-recording systems to minimise the need for double-entry.

GHG emissions estimation at farm/ enterprise-scale is increasingly being required within Farm Quality Assurance (QA) schemes. For example, the Agrecalc tool has been used since 2010 in the Scottish Beef Efficiency Scheme which is a voluntary government-run scheme paying suckler-beef producers who are actively engaged with improving productive efficiency. In Ireland, the non-commercial state body, Bord Bia, is responsible for a QA scheme that collects data as part of its audit process that allow productivity indices and carbon footprint to be calculated using the Teagasc Carbon Navigator tool.

One challenge for farm bench-marking is the provision of sufficient appropriate background data against which participating farms can robustly benchmark their performance. Lynch et al. (2018) reports an approach to use the robust representative FBS datasets of farm performance, based on detailed assessment of farm accountancy data, to assess environmental performance in parallel using modelling. This work showed variation in the calculated indicators resulting from differences in farm structure and management and within the range of expected values and hence the potential of this approach. There were also some weaknesses inherent in the approach as a result of the data being primarily focused on farm finances; for example, some management details were beyond the scope of standard data collection and hence were assumed the same for all farms: for example the number and type of field operations, which will have implications for a number of environmental impacts. Lynch et al. (2018) suggest that it would be relatively simple to add in data collection where the current FBS dataset cannot provide reliable estimates (for example, on management information for cover cropping, or establishment of new woodland). Data on agricultural land use returned to the EU integrated administration and control system (IACS) could also provide a useful, already routinely collected, data source to support estimation of crop / soil emissions.

The ability to generate detailed and reliable indicators of agricultural sustainability has been greatly enhanced over recent years as a result of increased collection and sharing of agricultural data. Co-operation across supply chains and between industry and state actors, with the integration of relevant databases held by each, can lighten the burden on farmers by minimising repeat data collection and enhance the accuracy of indicators by expanding the range of relevant data available for analyses. Remote sensing technologies enable further detail to be combined through, for example, geospatial integration of individual farms with satellite data, while the growth in on-farm monitoring technologies to aid farm management could provide further relevant data, if farmers agree to data-sharing. Despite this potential, these developments also present a number of significant challenges, including issues relating to data harmonisation, ownership and confidentiality. Unless data acquisition and use are sufficiently transparent, yet also able to maintain individual farm confidentiality where appropriate, there may be a loss of faith by farmers resulting in refusal for data to be shared, and ultimately a reduction in the ability to generate robust sustainability indicators (Lynch et al. 2018).

As well as providing an opportunity to support monitoring of impacts after adoption of mitigation practice on-farm, indicator frameworks can also provide input during the planning process allowing assessment of the impacts on farm of different mitigation practices (and their combinations). In this context, it is also useful to have a systematic approach that can reveal linkages between different aspects of sustainability. For many environmental impacts, potential associations with economic or social issues are unknown, and so assessing GHG impacts within a holistic sustainability assessment may prove important to identify any positive or negative trade-offs with production and farm profitability or other environmental impacts such as water quality (Lynch et al. 2019). At a larger scale such frameworks, may also allow EFI to interrogate the wider context of why environmentally beneficial actions may not have been adopted and may help communicate and encourage uptake.

5. Critical review/ synthesis

5.1. Opportunities and gaps

Areas and topics where EFI might develop evidence-reviews and translation materials rapidly

As part of the pilot development of EFI, this scoping review has confirmed that there is a body of high quality reviews linking the following interventions to net GHG in combinable cropping systems:

- Optimising N addition and avoiding N excess

- Actively growing ground cover in leaching risk periods + Use of catch and cover crops (considered together)
- Reducing intensity of cultivation
- Use of manures and composts
- Use of biosolids and industrial wastes
- Controlled release fertiliser/ inhibitors
- Use of biochar

Evidence translation activity is already well embedded for Optimising N addition (and avoiding N excess), through the Nutrient Management Guide (RB209) and other routes such as Tried and Tested, FACTS training for advisors. Although this is mainly focussed on optimising the costs of productivity, attention is paid to the risks of environmental impacts, including GHG emissions. The available evidence suggests that avoiding N excess by optimising N addition in fertilisers and manures reduces net GHG per unit production compared to cropping systems where N available is significantly greater than the crop N demand. Hence, where EFI develops an evidence summary for this intervention, routes for further dissemination are well established.

Use of catch and cover crops (considered together with Actively growing ground cover in leaching risk periods) is also an intervention where there is a clear evidence base (showing a reduction in net GHG where cover crops increase the period of the cropping cycle when the ground is covered by actively growing plants compared to cropping systems with periods where soil has limited ground cover. This results from both slow long-term increases in soil C storage and also reduction of nitrate losses from the system. There is also significant on-going work in developing underpinning guidance for practice. AHDB research projects and on-farm evaluation through the Farm Excellence programme have provided depth to the evaluation in practice of this group of interventions. AHDB has already begun work to bring together farmer-facing guidance on Cover cropping with a broad stakeholder group building on these research outputs. Here again, where EFI develops an evidence summary for this intervention, routes for further dissemination are well established.

Reducing cultivation intensity has been an area where evidence of the impact on soil C storage has been disputed, hence there have been a number of focussed research studies and systematic reviews targeting this question specifically. Under UK conditions (and in other temperate regions), the main impact of reduced cultivation intensity on soil C storage is to change the stratification of soil C storage, increasing C in surface layers, but reducing incorporation of C in deeper topsoil layers, rather than changing overall soil C storage. However, over the long term the impact on GHG emissions of the reduction in fuel use associated with reduced cultivation intensity is consistent and hence cumulatively significant. Therefore, the overall evidence suggests that reducing cultivation intensity reduces net GHG compared to cropping systems with conventional full-inversion plough-based primary tillage. AHDB has recently updated guidance for crop establishment in arable systems which provides a sound basis for practical decision-making on-farm about changes in cultivation systems. Current discussions about the value of no-till approaches in the agricultural industry (and the policy sector) often cite increases in soil C storage as a benefit. Hence, it is important to note that the adoption of conservation agriculture systems, combines both the use of catch and cover crops with no-till establishment and hence is very likely to reduce net GHG and increase soil C storage.

A long history of research into the use of organic materials whether manures, composts, bio-solids or industrial wastes) has shown that within a given soil and climatic regime, a linear relationship exists between C inputs in organic materials and soil organic matter where the soil is not close to the system's equilibrium maximum C storage level. Application of organic materials to arable land with low soil organic matter levels, if transport distances are low, is likely to have a greater benefit than application to grassland or other systems with soil organic matter levels close to the system's equilibrium maximum C storage level. However, such an increase in soil organic matter does not necessarily deliver a reduction in net GHG through soil carbon storage, if the material is simply being applied in a different location, it is not an additional transfer of C from the atmosphere to land. Where organic materials originate from outside the farm system 'boundary', a broader life-cycle assessment approach is needed, that considers the GHG impacts of: (1) offsite biomass removal, transport, and processing; (2) alternative end uses of the biomass; (3) interactions with other soil GHG-producing processes; and (4) synergies between these soil amendments and the fixation and retention of in situ plant-derived C. Any replacement of fertiliser N with N from organic materials is likely to result in a net reduction of GHG. However, there are also emissions, direct and indirect, from applications of organic materials (e.g. fuel used for transport, spreading) and these will partly offset the savings. Providing an EFI evidence summary for these interventions may therefore confuse, as much as help, practice and guidance with regard to soil organic matter (and soil health). AHDB has recently produced some farmer-facing guidance based on the long-term evidence base to support decision-making on the use of organic materials. One approach may be to provide an evidence synthesis that is more broadly focussed on Adopting long-term practices to increase soil carbon storage in the field; much of the relevant evidence base is already focussed at this level of intervention. This would draw out some of the underpinning factors to underpin best-practice guidance that addresses both sustainably increasing soil organic matter in arable soils (to benefit soil health and yield resilience) and also increasing soil C storage in the field. The emerging results from the AHDB-funded Rotations and Soil Biology and Soil Health Partnerships completing in 2021 would help to provide some evidence of evaluation in practice. Such technical information would also be of value to underpin carbon offsetting schemes for the private sector.

The use of controlled release fertiliser/ inhibitors and the use of biochar are not yet widely embedded practices in UK combinable cropping systems and there has been little evaluation in practice within the Farm Excellence network or more widely. However, products are available on the market and there is a robust research evidence base from which EFI could develop evidence summaries. Although there is less depth of information available, it would be possible to develop draft evidence summaries for:

- Biostimulants
- Integrating/ optimising N fixation in the rotation

The process of compiling and then discussing these evidence reviews with stakeholders would then help to highlight the key gaps in research evidence and/ or evaluations in practice.
There are on-going and recently completed research projects that are directly considering the impacts and opportunities of integrating grass/ herbal leys in rotations (in particular the SARIC-funded BB/R021716/1 which is expected to complete in October 2022) and opportunities for mitigating GHG losses from lowland peat (planned Defra research; NE/P014097/1 and PhD studentships). Hence for these topic areas it would make sense to align the development of evidence summaries with the emerging project findings.

Interventions to increase C storage through increasing trees and hedgerows, hedgerow management or agro-forestry have been relatively little reviewed in the research literature. However, there is a depth of knowledge available in research reports and practical guidance from the Woodland Trust. Hence for these topic areas it would make sense to align the development of evidence summaries with the activity of this NGO, and other relevant stakeholders, as this will also be an important route for dissemination.

As part of this project, evidence summaries were produced using the draft EFI Evidence Standards, to provide exemplars to support the next steps of EFI development. These draft documents are provided as Appendices:

- Optimising N addition and avoiding N excess (7.1)
- Actively growing ground cover in leaching risk periods + Use of catch and cover crops (considered together, 7.2)
- Reducing intensity of cultivation (7.3)
- Use of biostimulants (7.4)
- Use of organic amendments (7.5)

Areas and topics where more focused evidence is needed to underpin EFI

There is lack of direct evidence for cropping systems for interventions relating to the generation of renewable energy, replacement of fossil fuel energy and the interventions grouped in Objective 3 -

Boosting the green economy. There is a body of completed research tackling the issues of replacement of fossil fuel energy on farm but few peer-reviewed papers were found. The report of the EIP-AGRI focus group on renewable energy (EIP-AGRI 2019) provides a good foundation to develop a more focussed study on the practicalities, challenges and trade-offs amongst renewable energy technologies for use on-farm; such a study is likely to be of most value where it is cross-sector, rather than considered for arable farms alone.

The Supergen Bioenergy Hub (Phase 2 expected to complete in 2022) includes a wide range of research including the environmental impact of energy crop cultivation and waste management on soil carbon, GHG emissions and soil health, to assess impacts on farming systems and landscape. Work includes assessment of site selection (with a preference for allocation to land that is less effective for food production) and systems approaches to evaluate the wider socio-economic and environmental impacts. The BEACON Biorefining Centre of Excellence acts in a similar way to lead research on the conversion of biomass and biowastes into bio-based products with commercial applications. Co-ordination of EFI work in this area with these existing collaborations will allow added value opportunities to be developed.

5.2. Wider considerations for the Evidence for Farming Initiative

Whilst we recognised at the outset of this scoping study that a reduction in net GHG emissions for combinable cropping systems will be achieved most effectively by addressing all 3 objectives (improving productive efficiency, increasing C storage and boosting the green economy) in parallel on-farm, it is clear that not all mitigation interventions will be relevant, technically possible or cost-effective everywhere. Paustian et al. (2016) gave an example of a decision-tree for GHG mitigation in croplands that built from an assessment of the baseline conditions to guide adoption of changed practice that could also be profitable. Such an approach uses the intervention of land suitability mapping to inform decision making at the start of any process to plan how GHG mitigation could be delivered on-farm (Figure 6). In particular, identification and separate targeted mitigation management planning for drained cropped peat soils is important, as such soils may have very large GHG emissions but also often grow high-value crops. In addition, specific consideration of the management of non-cropped areas and those areas that are marginal (in terms of their returns, i.e. often deliver negative gross margins) may allow land use change options e.g. conversion of arable to grassland, woodland or renewable energy to be considered (Figure 6). Farmers are increasingly able to map gross margins within field as a result of the increased spatial resolution of data collection e.g. yield monitoring, precision use of inputs and this can allow the identification of marginal areas within fields (e.g. gravelly banks, seep/ flushes) where it may be most cost effective to take them out of production. There are still a broad range of interventions across all three objectives that can be considered for implementation as part of the profitable crop rotation (Figure

6). A decision-tree format to support the evaluation of options could provide one way-in for farmers/ advisors to access EFI information

EFI needs to be underpinned by a clear and transparent theory of change that will allow EFI to identify where, how and when to intervene to impact change in agricultural systems to deliver (in the pilot phases) mitigation of net GHG. It is also important to support consideration of GHG mitigation measures within a wider sustainability framework, particularly because of the trade-offs that may result e.g. the impact of use of crops supplying alternative biomaterials on ecological interactions (e.g. pollinators), herbicide and pesticide use. In their evidence gap mapping for agricultural innovation, Lopez-Avila et al. (2017) found that globally the effective dissemination of knowledge remains a challenge that prevents uptake of new (more productive) practices by farmers. Nonetheless they recognise a complex underlying theory of change where knowledge and the availability of required inputs combine to create innovation that is enabled through infrastructural support (practical, market, policy and financial). Hence the availability of knowledge alone will not enable change.

This scoping review has not been asked to review models of change for EFI, but as part of the review, the farming systems work of Giller et al. (2011) came to the review team's attention as a result of their review of conservation agriculture (Giller et al. 2015). They describe the DEED approach to combine farmer's local knowledge with science-based information gained though research by 1) Describing current production systems and their constraints; 2) Explaining the consequences of current practices and options on outputs and impacts using theory, on-farm experiments and modelling 3) Exploring options for agro-technological improvement using scenarios to analyse trade-offs, opportunities and constraints 4) Designing together with famers new management options.

The approach is embedded in the recognition that agronomic knowledge is fundamentally local and site-specific, but that the same time able to change and adapt in response to new knowledge learned. The heart of this process is co-learning – true knowledge exchange. Science and hence the evidence-base available for synthesis and systematic review is designed to answer "why does it work" questions and draw out common principles – hence the value of meta-analysis. However, for farmers the most important question is "will it work for me" and hence EFI will need an underpinning model that allows it to bring together evidence from science and practice effectively.

Giller et al. (2015) propose a system agronomy approach and working from the metaphor of not "forcing a square peg into a round hole", they describe the need for a two directional model of change where the matching of technologies to particular farmer circumstances involves:

(1) a selection and adaptation process of technology options suitable for the specific agro-ecological and socio-economic environment,

as well as,

(2) a process of understanding the drivers of farmer diversity to establish for which farmers the technical options may be suitable in a given environment.

In practice, many on-farm advisors will take a screening and evaluation approach with their clients and where this “bottom-up” knowledge about the implementation of GHG mitigation interventions can be harvested and shared then these evaluations in practice increase the depth of contextual understanding and add significant resolution to practical guidance. We have mapped the integrating roles of EFI and the AHDB Farm Excellence network (and other farmer research / advisory networks) into this framework (Figure 7). Giller et al. (2015) highlight he need to provide information in a non-prescriptive way so that it can be locally-adapted and suggest that this moves agronomy from looking for a one-size-fits-all (best bet) to allowing each system to identify their own best-fit. This model has emerged through happenstance in the review process and hence although it seems useful to these authors, it should be considered alongside other models and approaches as part of the EFI development process

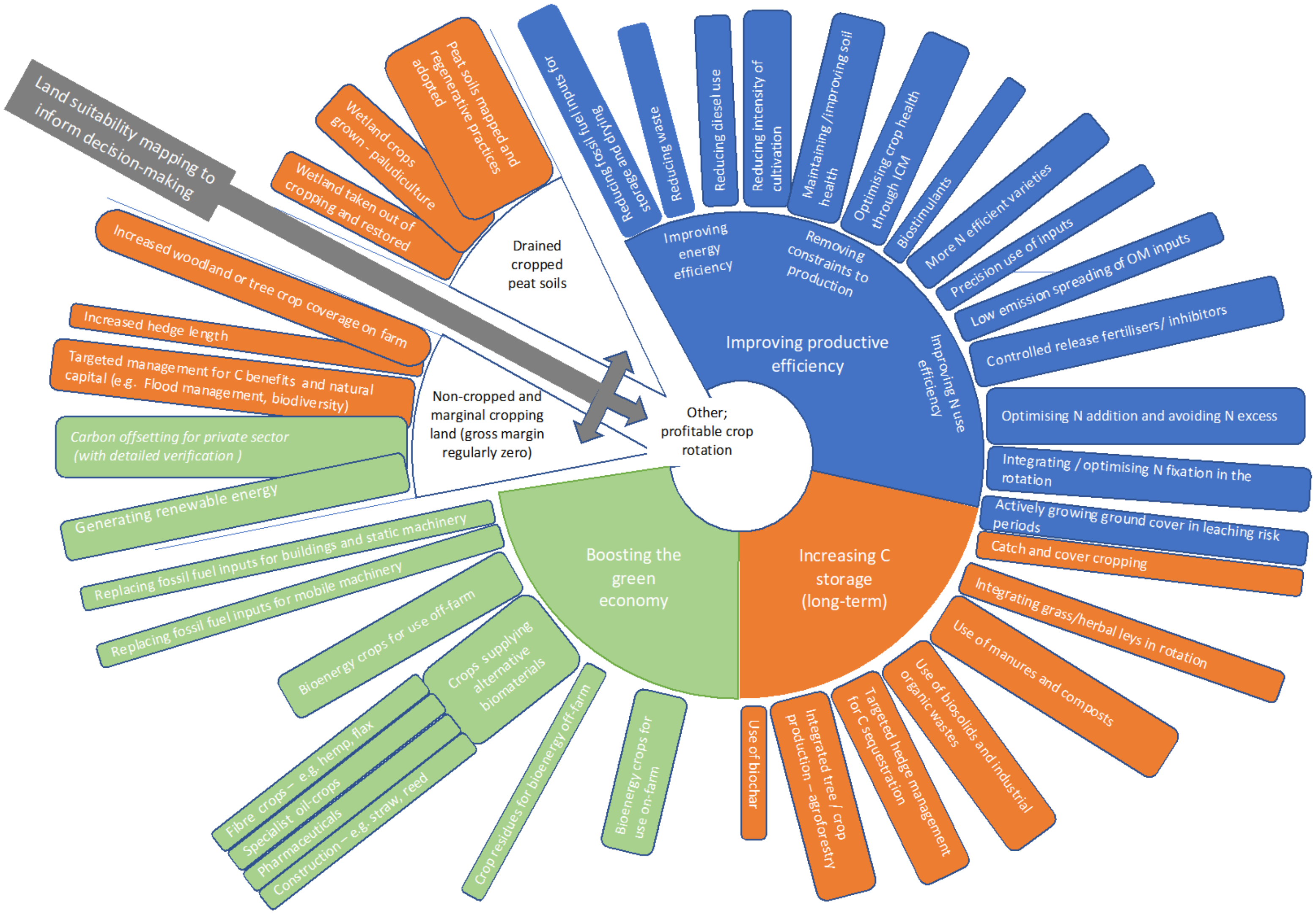
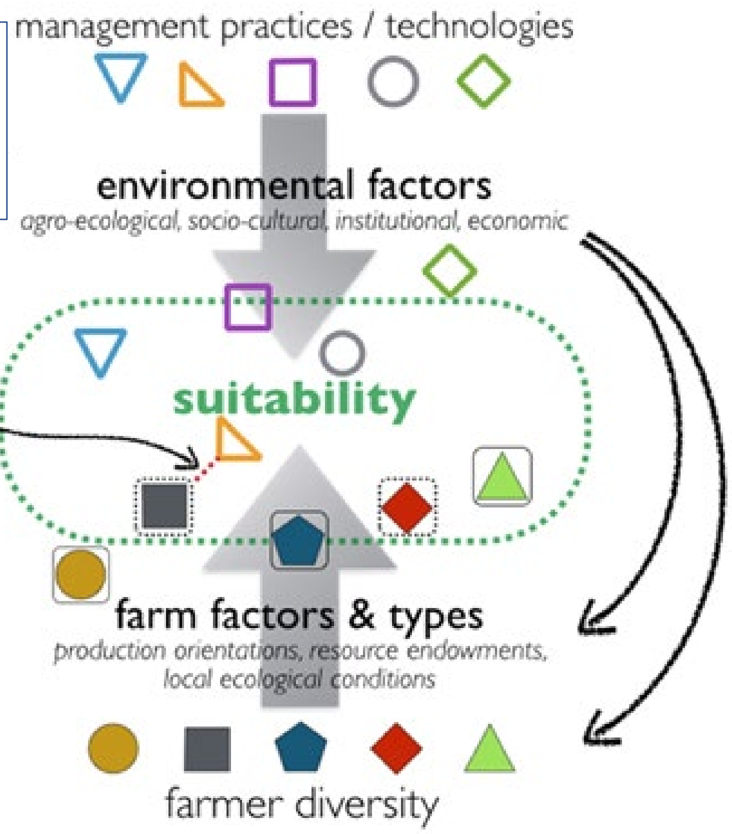


Figure 6 **Adaptation of the taxonomy of interventions for GHG mitigation as presented in Figure 1 to show the process of decision-making, based on the baseline conditions, as outlined in Paustian et al. (2016). It is important to first assess the amounts and locations of land in a profitable crop rotation, non-cropped or marginal cropping land and/or drained cropped peat soils. A different range of mitigation options may be suited to each.**

Selection and adaptation process of technology options suitable for the specific agro-ecological and socio-economic environment,

EFI



Farm Excellence
Innovative Farmers
+++
Processes to understand the drivers of farmer diversity and to establish with farmers how the technical options may be suitable in a given environment.

from "Best Bet" to "Best Fit" options.

Figure 7

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7. APPENDICES

7.1. Optimising N addition and avoiding N excess

Impact summary

Nitrogen (N) added in fertilisers and manures, together with that supplied by atmospheric deposition, mineralisation of soil organic matter and crop residues, and for leguminous crops, N fixation, meets and does not exceed the crop N demand.

Impacts

Reduced net GHG	++
Other impacts	
Cash crop yields	0

Cost

	£

How strong is the evidence?

Quality of research and evaluation	5
Relevance of context	3

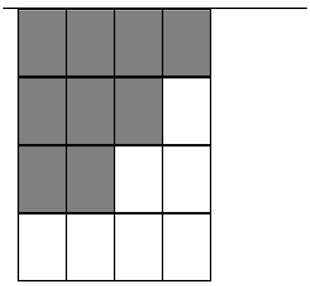
How much is known about?

How it works

Where it works

How to do it

What it costs



This is based on the strongest scores from a number of reviews

Optimising N addition and avoiding N excess - NARRATIVE SUMMARY

What is the intervention?

In the UK, crop yields are very commonly nitrogen (N)-limited so that yields are higher where N is added in fertilisers and/or animal manures. However, the response to N addition is not linear and shows a diminishing return, whether measured in terms of yield or in terms of economic return. Applying nitrogen in excess is therefore not cost-effective and increases the risk of losses by leaching and by microbial processes leading to N_2O emissions. The amount of N available to combinable crops is determined by the rates and timing of applications of synthetic fertilisers, animal manure, and for leguminous crops, biological N fixation. Other sources of N include atmospheric deposition and mineralisation of soil organic matter and crop residues. The theoretical optimum N is achieved when N supplied by all these sources matches the crop N demand. Site- and season-specific N recommendations (rate, timing, type, location) can be developed using best-practice guidance (such as the Nutrient Management Guide, RB209) but require grounded estimates of site/season- attainable yield and may need in-season adjustment.

The following narrative focuses on reviewing evidence that relates to the direct GHG emissions (focussed on N_2O) in cropping systems where N is added, through fertilisers and manures, and also takes account of reductions in indirect GHG emissions, where GHG emissions that are avoided due to lower rates of fertiliser use are taken into account.

Impacts relating to crop productivity are considered as these need to be taken into account where GHG emissions per unit production as considered.

Other impacts of N additions are not often noted in these reviews and no further impacts are summarised in the narrative. Impacts of organic manures (separately to their N supply) are considered in a separate narrative summary .

This narrative summary is based on 5 systematic/descriptive scientific reviews and 2 evaluations in practice that include information relevant to optimising N addition and avoiding N excess in temperate cropping systems.

There is some overlap between the primary research studies covered by the systematic/descriptive scientific reviews. The major systematic review on the impact of N fertiliser use on N_2O emissions reported in R5 provides a summary of all published work to that date. However, the later reviews deliberately build on the findings of R5 and included the earlier published work reviewed there in the updated meta-analyses.

EFFECT on net GHG

How effective is it?

Overall evidence suggests that avoiding N excess by optimising N addition in fertilisers and manures reduces net GHG per unit production compared to cropping systems where N available is significantly greater than the crop N demand. Evidence also suggests that small N additions can have positive benefits for net GHG compared with situations where crop yield is very limited by N availability.

All reviews note that although indirect GHG emissions (associated with fertiliser production) increase linearly with the amount of fertiliser N applied, measured N_20 emissions do not show a simple linear relationship with N addition (in fertiliser or manure). Differences between sites in N_20 emissions have been linked to rainfall (Evaluation 1 and 2) but Evaluation 2 also showed that there was a site-independent increase in N_20 emissions with fertiliser addition. Reviews 1, 3, 4 and 5 show a rapid increase in N_20 emissions where N availability markedly exceeds N demand; Evaluation 2 did not show this rapid increase where N application exceeded the measured optimum N application by 33-50% in the UK, although N_20 emissions did continue to increase with the increased N addition. Review 2 (considering fertiliser N application for maize systems in North America) suggested that to optimise N addition to reduce net GHG, N additions should be slightly lower than the recommendation typically made to attain the yield optimum (though without significant yield loss). Evaluation 2 also suggested that yield and N_20 emissions were co-optimised at fertiliser N applications around 70-80% of the N fertiliser recommendation made at the start of the growing season.

All reviews show that maintaining N addition so that overall N supply is close to the optimum has no effect on yield – compared with over-supply of 20-30%. In the few instances in UK arable systems, where crop yield is very limited by N availability, increasing N additions so that overall N supply is optimum will increase yield.

How strong is the evidence?

High quality systematic reviews and meta-analysis underpin much of the evidence focussed on the links between N additions, yield and N_20 emissions. Systematic reviews 2 and 4 focus even more closely on the relationship between N additions, N uptake (hence also N excess) and N_20 emissions. The impact of moderating factors was able to be taken into account through analysis in many of the reviews. The mechanisms underpinning the relationships between N addition and N_20 emissions are described and evaluated through meta-analysis in Review 5. Syntheses in Evaluation 1 bring together N_20 emissions data collected over 2 years or more in a network of European experiments.

MECHANISM

How does it work?

Overall the reviews provide a full description of the underpinning theory linking N additions and N_20 emissions. Review 5 provides a clear description of the conceptual “hole in the pipe” model and verifies the model through the subsequent data analysis. Overall the reviews clearly show that net GHG does not increase linearly as N addition increases from zero. Where no N is added, soils often have small net GHG. As the rate of N addition is increased, yield increases but net GHG does not increase as rapidly, so the net GHG per unit production reduces. However, as the rate of

N addition increases the N use efficiency (additional yield per unit N added) reduces and where N is surplus to crop demand, then both leaching losses and N_2O emissions increase rapidly.

In a final version, it might be useful to have a graphical presentation of these relationships; this could be adapted from Review 4

The model considers N_2O and NO emissions from agricultural soils as like the fluid coming out through a leaky pipe. The overall flow of N through the pipe for plant uptake is primarily determined by the application of N in fertilisers and animal manure, and biological N fixation by leguminous crops. Other sources of N include atmospheric deposition and mineralisation of soil organic matter and crop residues. The speed of the N flow through the pipe is strongly related to temperature, which controls soil processes at all levels by governing the microbial processes that underpin organic matter decomposition, denitrification, and nitrification rates. The size of the holes is determined by many factors such as soil water and oxygen, and gas diffusion (which depend on soil texture and drainage status) and pH. The importance of the holes in the pipe is determined by the N flow rate. At low levels of N flow the NO and N_2O losses will be low regardless of the size of the holes. But if N flow is high then the losses of N relative to the flow will be determined by the size of the holes – so the same N supply at different sites can lead to different N_2O and NO emissions.

WHERE IT WORKS

Overall the reviews provide a theoretically grounded description of relevant contextual conditions which could affect the relationship between N additions and N_20 emissions. However, despite differences in the magnitude of N_20 emissions between sites/seasons, the basic relationship between N excess (surplus over crop demand) and N_20 emissions was found to hold. However, the crop yields attained and actual N optimum varies with site/ season, therefore

ECONOMIC EVALUATION

None of the Reviews or Evaluations provide an economic evaluation. However, the economic benefits of optimising N additions have been clearly established in the agronomic literature over the past half century. Site- and season-specific N recommendations (rate, timing, type, location) can be developed for UK cropping systems using best-practice guidance (such as the Nutrient Management Guide, RB209) but require grounded estimates of attainable yield by site/season and may need in-season adjustment.

The final narrative summary would also include:

FARMER CASE STUDIES – experiences from AHDB Monitor farmers and other practitioners

GUIDANCE FOR ON-FARM PRACTICE e.g. The Nutrient Management Guide (RB209)

Available at: https://ahdb.org.uk/nutrient-management-guide-rb209

RESOURCES

REVIEWS

	First author	Date published	Title	DOI or web-link
R1	Yao, Z.	2020	Soil N intensity as a measure to estimate annual N_2O and NO fluxes from natural and managed ecosystems	10.1016/j.cosust.2020.03.008
R2	Omonode, R. A.	2017	Achieving lower nitrogen balance and higher nitrogen recovery efficiency reduces nitrous oxide emissions in North America's maize cropping systems	10.3389/fpls.2017.01080
R3	Shcherbak, I.	2014	Global meta-analysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen	10.1073/pnas.1322434111
R4	Van Groenigen, J.W.	2010	Towards an agronomic assessment of N_2O emissions: A case study for arable crops	10.1111/j.1365-2389.2009.01217.x
R5	Bouwman, A. F.	2002	Emissions of N_2O and NO from fertilized fields: Summary of available measurement data	10.1029/2001gb001811

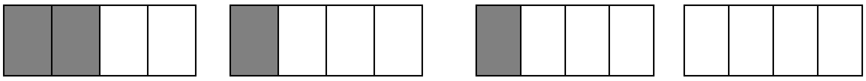
EVALUATION IN PRACTICE

	First author	Date published	Title	DOI or web-link
E1	Rees, R. M.	2013	Nitrous oxide emissions from European agriculture - An analysis of variability and drivers of emissions from field experiments	10.5194/bg-10-2671-2013
E2	Bell, M.J.	2015	Nitrous oxide emissions from fertilised UK arable soils: fluxes, emission factors and mitigation.	10.1016/j.agee.2015.07.003

Description and rating of individual reviews

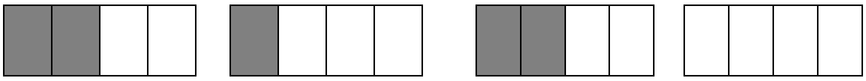
R1 is a data synthesis and meta-analysis of the relationship between soil nitrate concentration (annual weighted mean) and N_2O emissions across a range of land uses including fertilised cropping systems

Credibility	How it works	Where it works	How to do it	What it costs
Strong				



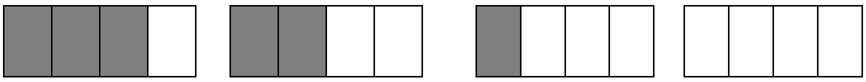
R2 is a data synthesis and meta-analysis of how fertiliser management factors affect N efficiency, N surplus and N_20 emissions for maize systems in North America. It includes consideration of the practical implications for fertiliser recommendation and field management.

Credibility	How it works	Where it works	How to do it	What it costs
Strong				



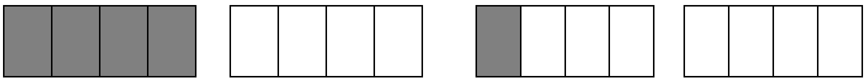
R3 is a systematic review with meta-analysis which examines whether the Emission Factor (N20 emitted per kg N applied) changes with N application rate. Meta-analysis considers the effect of soil, crop and climate factors.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong				



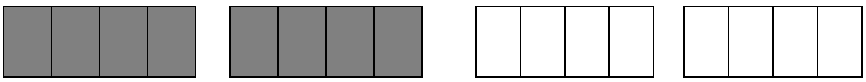
R4 is a systematic review and meta-analysis of the relationship between fertiliser N input, crop N uptake and emissions of N_2O. The meta-analysis is used to evaluate proposed theoretical frameworks explaining the relationship and to highlight implications for fertiliser management.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong				



R5 is a major systematic review and meta-analysis of the factors affecting emissions of N_2O and NO from fertilized systems including grassland. It provides estimates of the fertiliser-induced emission factor.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong				



E1 is a synthesis of data from a network of agricultural experiments (15; 8 in arable systems) in Europe where N_2O emissions were measured. The data synthesis is used to analyse variability, identify drivers of emissions and explore the relative importance of management, climate and site factors in controlling emissions.

UK farm relevance	How it works	Where it works	How to do it	What it costs
Moderate	■■■□	■■□□	■□□□	□□□□

E2 is a synthesis of data from a UK network of agricultural experiments (3) where N_2O emissions were measured in 2011/12. The data synthesis is used to measure Emission Factors (N_20 emitted per kg N applied) and identify the impact of management, climate and site factors in controlling emissions.

UK farm relevance	How it works	Where it works	How to do it	What it costs
Moderate	■■■□	■■□□	■□□□	□□□□

7.2. Actively growing ground cover in leaching risk periods + Use of catch and cover crops

Impact summary

Growing a crop to avoid periods of bare soil after the cash crop is harvested and before the following cash crop, often overwinter.

Impacts

Reduced net GHG	**++**
Other impacts	
Increased soil organic matter	**++**
Reduced N leaching	**++**
Reduced run-off and sediment loss	**++**
Cash crop yields	**+/-**

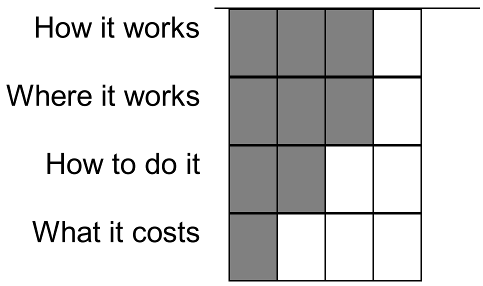
Cost

	££

How strong is the evidence?

Quality of research and evaluation	**5**
Relevance of context	**5**

How much do the reviews tell us about?



This is based on the strongest scores from a number of reviews

Cover cropping - NARRATIVE SUMMARY

What is the intervention?

Cover crops (also known as catch crops) are plants grown after the cash crop is harvested. This avoids periods of bare soil which are associated with greater risk of erosion and nitrogen leaching. Cover cropping can comprise a single species or a mixture of species and a wide range of species are currently used. Cover crops can be terminated (by herbicides or cultivation) in winter or spring, or grazed, and incorporated in soils by tillage to prevent competition with the following cash crop, and to promote mineralisation of organic N. They can also be left on the soil surface until a spring crop is direct-drilled, to provide weed control and N inputs.

The following narrative focuses on reviewing evidence that relates to the direct GHG emissions (focussed on N_2O) and changes in C storage in soils in cropping systems with cover cropping, and reductions in indirect GHG emissions, if nitrate losses by leaching are reduced.

Impacts relating to productivity of cash crops are considered, where they are covered by the reviews, as these have an impact on the economics of adoption. A range of other impacts of cover cropping are noted in these reviews and hence are summarised briefly in the narrative. Impacts of cover cropping on weed control, interactions with biodiversity, pests and beneficials are considered more extensively in other reviews and are not reviewed here but would be important considerations for farmers considering adoption.

This narrative summary is based on 9 systematic/descriptive scientific reviews and 4 evaluations in practice that include information relevant to the use of cover crops in temperate cropping systems.

There is some overlap between the primary research studies covered by the systematic/descriptive scientific reviews, and in some cases, later reviews deliberately build on the findings of the earlier published work.

EFFECT on net GHG

How effective is it?

Overall, evidence suggests that the use of cover crops to increase the period of the cropping cycle when the ground is covered by actively growing plants reduces net GHG compared to cropping systems with periods where soil has limited ground cover.

Review 1 conducted a meta-analysis of the net GHG emissions taking direct N_20 emissions, changes in soil C storage and indirect N_20 emissions into account. The reduction in net GHG due to cover crops, compared to the control treatments, was 2.06 ± 2.10 t CO_2-eq /ha per year with no significant difference between cover crop types. Review 1 highlighted the importance of increases in C storage in soil and the reduction in indirect N_20 emissions resulting from losses of N through leaching, with little change in direct N_20 emissions.

Review 4 showed that the impact on net GHG emissions was the result of a mix of +ve and -ve contributing processes; but with the main impact arising from increased soil C storage and N supply from legume cover crops (allowing reduced N fertiliser use for the cash crop) as the main drivers.

All reviews that considered the impact of cover crops on soil C storage (Reviews 1, 2, 3, 4, 5, 9) showed an increase in soil organic matter where cover crops were used. Review 9 conducted a focussed meta-analysis and found that cover crops increase soil organic in topsoil slowly C (0.32 t C /ha per year) over the long-term. Review 9 used modelling to show that this slow increase would continue for >100 years; data synthesis in Review 3 also showed that the relative effect of cover cropping on soil organic matter increases with time since the introduction of cover cropping. Review 5 showed that the increase in soil organic C from cover cropping over the long-term, can partly, but not wholly offset the impacts of removing crop residues (e.g. for livestock bedding or biofuels) on soil organic C.

All reviews that considered the impact of cover crops on nitrate leaching (Reviews 1, 2, 3, 6) showed a marked reduction in N losses with all types of cover crops. Review 6 showed that good cover rather than a cover crop *sensu strictu* was the most important factor reducing N leaching; weedy fallow could give N leaching reductions at lower costs.

Review 4 also showed a small change in albedo in cropping systems with cover cropping which would reduce warming impacts.

Meta-analysis in Review 1 showed that cover crops did not significantly increase N_20 emissions (28 comparisons). Review 8 found that while most studies synthesised reported no effects of cover crops on N_2O emissions, a few studies found increased N_2O fluxes. Review 2 identified interactions between cover crop use, tillage, and season which determined whether cover crops were net sources or sinks of N_2O over their life-cycle.

Reviewer 3 identified cases where long-term use of cover crops increased direct N_2O emissions from these cropping systems. Reviewer 4 presented seasonal data for N_2O emissions in cover crop systems and showed periods of positive emission associated with cover crop incorporation and residue decomposition. All the reviews that considered direct N_2O emissions found that over the growing season, N_2O emissions that are associated with the cover crops are very low (close to zero).

How strong is the evidence?

High quality systematic reviews and meta-analysis underpin much of the evidence, though often focussing on aspects of the GHG balance in cover cropping (Reviews 1, 5, 6, 9). Robust data synthesis (Reviews 3 and 8) and the application of data in case studies or through modelling approaches provide further depth to the evidence base (Reviews 2, 4, 7). These syntheses bring together data from a very large number of controlled studies or robust paired comparisons often over the long-term (>10 years). Differences in cover crop types, climates and soil types were able to be taken into account in the analysis in many of the reviews.

Some assumptions and conversion factors are needed to take measured data e.g. of nitrate leaching or soil C storage and express these in terms of GHG emissions. These are based on agreed IPCC conversion factors.

OTHER EFFECTS

Review 1 showed that overall cover crops significantly decreased grain yield (by 4% on average) of the cash crops compared to the control treatments (154 comparisons). In contrast Review 7 also showed a small yield increase which increased with time after cover crops were introduced to the rotation. Review 1 found that there were differences with cover crop type - legume–non-legume mixed cover crops significantly increased grain yield of the cash crop (by c. 13%; only 6 comparisons) and legume cover crops increased grain %N in cash crops (15 comparisons). Review 3 showed a small relative yield increase after legume cover crops in low-input systems.

Evaluation in practice (Evaluation 2 and 3) reported small positive benefits to crop yields across the rotation in most cases, but also catastrophic yield reductions due to poor cash crop establishment following cover crops.

Review 3 showed relative benefits from cover crops in reducing erosion, run-off and drainage, and in improving soil microbial activity and arbuscular mycorrhizal fungal colonisation in the following cash crop. Review 8 also highlighted consistent large reductions in run-off and sediment losses as well as highlighting the positive impact of cover cropping on soil structural and hydraulic properties across multiple studies. Review 8 stresses that the magnitude and balance of benefits from cover cropping are highly site-specific.

MECHANISM

How does it work?

Overall the reviews provide a full description of the theory of change drawn from prior work and testable predictions generated from it. Review 1 provides a comprehensive summary of the interacting mechanisms by which introducing cover crops to cropping systems leads to changes in net GHG emissions. Review 7 puts these processes into a clear UK agronomic context.

Replacing fallow periods with cover crops is an effective management practice to withdraw soil N into the biomass of the cover crops and to reduce nitrate leaching, which is a cause of indirect N_2O emissions. However, cover crops could increase direct N_2O emissions by increasing the photosynthetically derived C supply from actively growing root systems and/or when residues are incorporated into the soil. Cover crops can also increase SOC stocks in agricultural soils, since more C and N are added to the soil pools through roots and in cover crop residues. Reviews 8 and 9 provide more detail of the soil processes and controlling factors that determine whether added organic materials in cover crop roots and residues increase soil organic matter; soil type has only a limited impact on the effect. Review 4 also highlights the potential for displacement of N fertiliser use as a result of mineralisation of N from cover crop residues.

In a final version, it might be useful to show some of the interacting roles of cover crops; this could be adapted from figures in Review 8

WHERE IT WORKS

Overall the reviews provide a theoretically grounded description of relevant contextual conditions which determine where/ when cover cropping works. Theoretical understanding is coupled with a number of syntheses of evaluations in on-farm practice. Overall the reviews provide concerted efforts to document implementation and the challenges associated with implementation in practice.

Reviews 1 and 8 found that the major problems with the integration of cover crops into cropping systems appear mostly in dry environments (<500 mm annual rainfall) where water storage in soils declines with the establishment of cover crops, and results in reduced following crop yields. Some areas in south-east England are close to this rainfall level and in some years, low winter rainfall would increase this risk on light /shallow soils with low water holding capacity. In practice, Evaluation 2 found that cover cropping on heavy textured soils in the UK gave more issues due to increased topsoil moisture, probably due to the crop cover preventing surface evaporation. In these circumstances and depending on the weather, late destruction (late March/early April) and incorporation of a high cover crop biomass (less than one week prior to drilling the cash crop) can result in a poor seedbed for subsequent cash crop establishment, leading to lower crop yields.

Evaluation 2 found that at the farm level in the UK, seasonal factors (soil moisture condition) had a greater impact than any specific cover crop mix, drilling date, destruction or following crop in determining cover crop effectiveness.

Reviews 1 and 7 found that the most important agronomic factor for achieving benefits for cover crops was the timing of establishment (late summer/early autumn in the UK); this was confirmed in practice in Evaluation 2. Review 6 identified the importance of achieving good ground-cover (estimated from cover crop biomass) but showed the same benefits from a weedy fallow as from cover crops with the same ground cover. Review 1 found that cover crops were most efficient in reducing N leaching when soil structure was good (BD was <1.4g /cm^3 so not restricting rooting).

Review 1 found greatest reduction in leaching where N fertiliser application rate was >200 kg N /ha per year on average so that there was some residual or mineralising N at leaching risk. Review 2 showed that non-legumes either as sole cover crops or in mixtures with legumes were effective at reducing N leaching – but found that sole legumes were less effective. Review 3 also showed higher levels of soil nitrate after legume cover crops. However, the fertiliser N benefit of legumes is higher (Review 4). Review 7 highlighted that N fixation is most effective between 7°C and 20°C which means that in most seasons, little N is usually fixed over-winter. Evaluation 1 found no clear benefit of mixes over sole species cover crops.

Review 1 showed that the timing and location of non-legume cover crops in the rotation need to be considered carefully to avoid competition with the primary crop. Review 7 found that cover crops with allelopathic effects include several cereal and brassica species, buckwheat, clovers, sorghum, hairy vetch, sunflower and fescues. Review 7 showed the negative impacts of a brassica cover crop on immediately following brassicas and Evaluation 2 highlighted a negative impact of growing a cereal cover crop (oats and particularly rye) on the subsequent performance of spring barley. Evaluation 4 identifies some promising cover crops to meet different farmer priorities for key climate/farming-system combinations in the USA.

Evaluation 2 found the most cited reasons by farmers for not growing cover crops were: (i) they did not fit with the current rotation (ii) expense and (iii) difficulty of measuring their benefit to crop production. Evaluation 3 found that incorporation of cover crop residues was the greatest challenge for farmers growing cover crops; a lack of equipment, especially for no-till systems, influenced their decisions about cover cropping.

ECONOMIC EVALUATION

Overall the reviews, provide limited information on direct or indirect economic costs and benefits. Review 1 and Review 3 identify the likely areas of direct cost and potential benefits, but no economic assessments are made. Evaluation 4 also only assessed costs and benefits in general terms. Cover crops increase management costs, due to the need to purchase seed, management operations and termination costs, Review 7 found that over 5 seasons, small yield benefits covered the costs of cover crop seed and establishment. However, Evaluation 2 found a reduction in margin compared to no cover crops for cumulative (two-year) margins for all but one of the comparisons (20 comparisons at seven study sites).

Evaluation 3 found that the costs of cover cropping were not considered an obstacle to implementation by farmers. Review 1 and 3 highlight the need to consider the costs in relation to the wider potentially realisable benefits including retention and carryover of nutrients between phases of a rotation, and the opportunity for the cover crops to be sold as forage or grazed.

Evaluation 2 has some reference to the current payment schemes and options, but I have not included this as it would date very quickly …a link to this information could be provided in the guidance section.

The final narrative summary would also include:

FARMER CASE STUDIES - experiences from AHDB Monitor farmers and other practitioners. For example seven AHDB case studies are available at: https://ahdb.org.uk/cover-crops

GUIDANCE FOR ON-FARM PRACTICE e.g. Opportunities for cover crop in conventional arable rotations. Available at: https://ahdb.org.uk/cover-crops

RESOURCES

REVIEWS

	First author	Date published	Title	DOI or web-link
R1	Abdalla, M.	2019	A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity	10.1111/gcb.14644
R2	Hansen, S.	2019	Reviews and syntheses: Review of causes and sources of N_2O emissions and NO_3 leaching from organic arable crop rotations	10.5194/bg-16-2795-2019
R3	Daryanto, S.	2018	Quantitative synthesis on the ecosystem services of cover crops	10.1016/j.earscirev.2018.06.013
R4	Kaye, J. P.	2017	Using cover crops to mitigate and adapt to climate change. A review	10.1007/s13593-016-0410-x
R5	Ruis, S. J.	2017	Cover crops could offset crop residue removal effects on soil carbon and other properties: A review	10.2134/agronj2016.12.0735
R6	Wortman, S. E.	2016	Weedy fallow as an alternative strategy for reducing nitrogen loss from annual cropping systems	10.1007/s13593-016-0397-3
R7	AHDB - RR90	2016	A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species	https://ahdb.org.uk/a-review-of-the-benefits-optimal-crop-management-practices-and-knowledge-gaps-associated-with-different-cover-crop-species
R8	Blanco-Canqui, H.	2015	Cover crops and ecosystem services: Insights from studies in temperate soils	10.2134/agronj15.0086
R9	Poeplau, C.	2015	Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis	10.1016/j.agee.2014.10.024

EVALUATION IN PRACTICE

	First author	Date published	Title	DOI or web-link
E1	Chapagain, T.	2020	The potential of multi-species mixtures to diversify cover crop benefits	10.3390/su12052058
E2	AHDB – PR620	2020	Maximising the benefits from cover crops through species selection and crop management	https://ahdb.org.uk/maximising-the-benefits-from-cover-crops-through-species-selection-and-crop-management-maxi-cover-crop
E3	O'Connell, S.	2014	A survey of cover crop practices and perceptions of sustainable farmers in North Carolina and the surrounding region	10.1017/S1742170514000398
E4	Snapp, S. S.	2005	Evaluating cover crops for benefits, costs and performance within cropping system niches	None found (available via Research gate)

Description and rating of individual reviews

R1 is a systematic review with meta-analysis across 106 studies (372 sites). The analysis is global but with identification of climate groupings; 68% of sites are in temperate cropping systems and hence UK-relevant.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong	■■■□	■■■□	■□□□	■□□□

R2 is a descriptive review bringing together data from 4-8 studies on N_2O emissions and nitrate leaching in organic cropping systems in temperate climates.

Credibility	How it works	Where it works	How to do it	What it costs
Moderate	■■■□	■■□□	■□□□	□□□□

R3 is a systematic review which quantifies the relative effect of a cover crop in relation to a fallow/ no cover system on a broad range of ecosystem services including GHG emissions, soil organic matter and nitrate leaching across 377 studies globally.

Credibility	How it works	Where it works	How to do it	What it costs
Strong	■■□□	■■□□	■□□□	■□□□

R4 is an integrative synthesis which uses existing meta-analyses, measurements and modelling to provide an integrated assessment of each component and the overall GHG balance in two case study rotations (based on those seen at long-term trials sites with measurements). One cropping system is temperature (cool moist) cropping comparable to the UK; one is an irrigated Mediterranean cropping system.

Credibility	How it works	Where it works	How to do it	What it costs
Moderate	■■■□	■■■□	■■■□	□□□□

R5 is an integrative synthesis which carries out a focussed synthesis of available data on the impacts of crop residue removal on soil organic carbon in temperate annual cropping systems with and without cover crops in the rotation.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong	■■□□	■□□□	■■□□	□□□□

R6 is a systematic review with meta-analysis across a focussed sub-set of data which allowed a comparison of a weedy fallow with cover crops and/or bare fallow in terms of impacts on nitrate leaching.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong	■■□□	■■□□	■■□□	□□□□

R7 is a descriptive review developed to underpin practical guidance to UK farmers; literature review is used to summarise and synthesise data which are also assessed in an agronomic cost/benefit analysis.

Credibility	How it works	Where it works	How to do it	What it costs
Moderate	■■□□	■■■□	■■■□	■■□□

R8 is a descriptive review of the potential multi-functional benefits of cover crops with some data collation (8-17 comparisons) for some of the benefits assessed where data were available.

Credibility	How it works	Where it works	How to do it	What it costs
Strong	■■■□	■■■□	■□□□	□□□□

R9 is a systematic review which use a focussed meta-analysis to evaluate the impact of cover crops on soil organic carbon. A modelling approach is used to estimate the time to saturation and contributions to overall GHG mitigation are estimated.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong	■■■□	■■□□	□□□□	□□□□

E1 is a descriptive review drawing from evaluations in practice of cover cropping in cool temperate regions and presenting guidelines for development of a complementary cover crop mixture to meet site-specific needs .

UK farm relevance	How it works	Where it works	How to do it	What it costs
Strong	■■□□	■□□□	■■■□	□□□□

E2 is the report of a series of large plot trials, validation trials on-farm and a compilation of farmer experiences of the use of cover crops within cropping systems in the UK.

UK farm relevance	How it works	Where it works	How to do it	What it costs
Very strong	■□□□	■■■□	■■■□	■■□□

E3 is the report of a farmer survey of farmers using cover cropping to identify the range of practices and perceptions of their impacts.

UK farm relevance	How it works	Where it works	How to do it	What it costs
Moderate	■□□□	■□□□	■■■□	■■□□

E4 is a descriptive review which links knowledge from the literature and from farmer practice to identify promising cover crops to meet different farmer priorities for key climate/farming-system combinations in the USA.

UK farm relevance	How it works	Where it works	How to do it	What it costs
Strong	■■□□	■□□□	■■■□	■■□□

7.3. Reducing intensity of cultivation

Impact summary

Moving away from a plough-based establishment systems or cultivation approaches that require many passes to create a seed-bed.

Impacts

Reduced net GHG	**+**
Other impacts	
Increased topsoil organic matter	**+**
Increased soil bulk density	**++**
Increased weed density	**+**
Cash crop yields	**+/-**

Cost

	£££

How strong is the evidence?

Quality of research and evaluation	**5**
Relevance of context	**4**

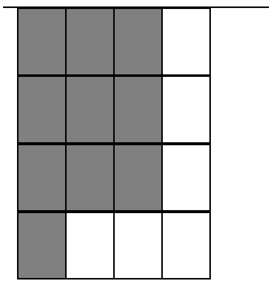
How much do the reviews tell us about?

How it works

Where it works

How to do it

What it costs



This is based on the strongest scores from a number of reviews

Reducing intensity of cultivation - NARRATIVE SUMMARY

What is the intervention?

Cultivation (also known as tillage) is comprised of a number of mechanical operations that change soil structure. It is used as an agronomic tool for seed-bed preparation and weed-control. A range of cultivation equipment working at a range of depths is used on UK farms. These field operations are a major part of the cost, labour and fuel consumption associated with cropping systems. Reductions in cultivation intensity have also been promoted as a means to improve soil health.

The following narrative focuses on reviewing evidence that relates to the direct GHG emissions (focussed on N_2O) and changes in C storage in soils in cropping systems with reduced cultivation intensity, and reductions in indirect GHG emissions, where CO_2 emissions that are avoided from reduced diesel use are taken into account.

Impacts relating to crop productivity are considered as these would need to be taken into account where GHG emissions per unit production are considered and they will also have an impact on the economics of adoption.

A range of other impacts of reducing cultivation intensity are noted in these reviews and hence are summarised briefly in the narrative. Impacts of cultivations on weed control, erosion risk, labour requirements are discussed in Evaluations 2 and 3, but were not the focus of the systematic literature search and are therefore not covered by the Reviews but would be important considerations for farmers considering adoption.

This narrative summary is based on 7 systematic/descriptive scientific reviews and 3 evaluations in practice that include information relevant to reducing intensity of cultivation in temperate cropping systems.

There is some overlap between the primary research studies covered by the systematic/descriptive scientific reviews. The major systematic review on the impact of cultivation intensity on C storage in soil reported in R2 does not include any of the earlier published reviews of the same topic within its reference list. However, in some cases, later reviews deliberately build on the findings of earlier published work.

EFFECT on net GHG

How effective is it?

Overall, evidence suggests that reducing cultivation intensity reduces net GHG compared to cropping systems with conventional full-inversion plough-based primary tillage. Over the long term the impact on GHG emissions of reduction in fuel use is constant and hence cumulatively significant over the long-term.

Whilst it seems obvious that reducing cultivation intensity will reduce fuel use, few studies have made an explicit assessment of the effect of fuel consumption on GHG emissions associated with cultivation; for a USA-based synthesis, Review 7 calculated the emissions from cultivations and harvesting for conventional plough-based (0.07 t C /ha), reduced tillage disk-based (0.04 t C /ha) and zero-tillage (0.02 t C /ha) establishment approaches for combinable cropping.

In the past, there have been mixed claims about the impact of reducing cultivation intensity on soil C storage. Robust meta-analysis (Review 1 and 2) assessing the impact of reducing cultivation intensity on soil C storage in the boreo-temperate zone showed that reducing tillage intensity increases soil C storage only in the topsoil (0-30 cm) with effects detectable by field measurement after 10 years of implementation; the estimated annual increase when changing from high-intensity plough-based tillage system to intermediate intensity or to no-tillage was c. 0.33 and 0.4 t C /ha per year respectively which is expected to continue for c. 40 years (Review 6). Increased soil C storage in the topsoil was also found where tillage intensity was reduced in organic farming systems (Review 3). However, Reviews 1 and 2 found that change in soil C storage were not detectable when the soil profile is considered (0-60 cm depth) indicating that the changes in topsoil are mainly due to differences in stratification rather than an overall increase in the soil C storage. Under UK conditions, changes in the stratification of soil C storage as a result of reducing tillage intensity, rather than overall soil C storage are now confirmed (Evaluation 1).

Review 4 highlighted that adopting reduced or no-till may also affect emissions of N_2O, but the net effects are inconsistent and not well-quantified.

Robust meta-analysis (Review 5) has shown that there is a small but significantly lower yield of cereals in rainfed temperate no-till systems compared with plough-based tillage (– 3-4%), similar yield differences were found in UK long-term experiments (Evaluation 1); hence the net GHG reduction is reduced if expressed on a per unit product basis. When gross margins (£) were considered at a cropping system level (Evaluation 1), reductions in yield were more than offset by the reduced costs of establishment with lower cultivation intensity.

How strong is the evidence?

High quality systematic reviews and meta-analysis underpin much of the evidence, though the main review effort has focussed on assessing the impact on soil C storage where cultivation intensity is reduced (Reviews 1, 2, 3). Differences in climates, soil types, duration of comparison, soil sampling depth and some other moderating factors were able to be taken into account in the analysis in many of the reviews. The mechanisms affecting soil C storage are described in detail in Review 4. A review of similar quality and depth is also included that assesses the impact of no-till establishment on crop yield (Review 5). These syntheses bring together data from a very large number of controlled studies in long-term studies (>10 years). Robust data synthesis at the cropping system level (Review 7) and the application of data together with modelling approaches (Review 6) provide further depth to the evidence base.

Some assumptions and conversion factors are needed to take measured data e.g. fuel use, soil C storage and express these in terms of GHG emissions. These are based on agreed IPCC conversion factors.

OTHER EFFECTS

Review 5 showed that reducing cultivation intensity reduced grain yield slightly, but significantly. Yield reductions were also shown in organic farming systems (Review 3) where increasing weed density was also found with reduced tillage intensity. Review 4 and Evaluations 2 and 3 show how increased attention and inputs for grass weed control are required where plough-based systems are replaced by establishment with reduced cultivation intensity.

Evaluation 3 showed that cropping systems with reduced tillage compared with ploughing, substantially decreased sediment loss in run off, nitrate leaching, total and soluble P losses, and herbicide loss in drainage. Evaluation 2 clearly showed that that the magnitude and balance of benefits from reducing cultivation intensity are site- and season-specific.

MECHANISM

How does it work?

Overall the reviews provide a full description of the theory of change drawn from prior work and testable predictions generated from it. Review 4 provides a clear description of the mechanisms determining how cultivation intensity affects soil properties and soil C storage as well as GHG fluxes. Review 6 found that even where occasional more intensive cultivation is needed to address compaction or for weed control much of the benefit in terms of soil C storage in the topsoil is maintained.

Fewer and less intense cultivation operations require less fuel. Cultivation operations affect soil structure by deliberately breaking soil aggregates. In conventional tillage operations, crop residues are mixed with the soil and the plough layer become relatively homogenous in terms of soil structure, nutrient and soil C storage. Cultivation operations also negatively affect soil macro-fauna such as earthworms. Where cultivation intensity reduces, soil C accumulates closer to the surface due to the reduced physical mixing and, at the same time, reduction in cultivation intensity reduces the exposure and oxidation of soil C and increases aggregate stability. Weed seeds are not buried through cultivation where ploughing is no longer used.

WHERE IT WORKS

Overall the reviews provide a theoretically grounded description of relevant contextual conditions which determine where/ when reduction in tillage intensity can be achieved most successfully (Evaluation 2) and where it has most benefits for topsoil organic matter (Reviews 1 and 2) and least impact on crop yield (Review 5) .

The Evaluations provide some assessment of on-farm practice, mainly in large-plot trials managed by farmer/ researcher teams. Overall the reviews provide limited information on the range of implementation in the UK and the challenges associated with implementation in practice. Evaluation 2 found that reducing the intensity of cultivation is more easily and most effectively adopted by large farms on with well drained soils of stable structure (clays, medium loams and chalk and limestone soils) in areas of moderate average annual rainfall (less than 630 mm) and an average return to field capacity date (full recharge of soil profile) later than 1 November. Because of the significant impact of poor crop establishment on crop growth, more careful planning and flexible management input is needed where reduced cultivation systems are used (Evaluation 2 and 3)

ECONOMIC EVALUATION

Overall the reviews, provide limited information on direct or indirect economic costs and benefits. Evaluations 2 and 3 identify the need for capital investment in machinery alongside the reduced annual establishment costs, but no economic assessments are made.

The final narrative summary would also include:

FARMER CASE STUDIES - experiences from AHDB Monitor farmers and other practitioners.

Case studies from the Soil Management Initiative could be refreshed - http://adlib.everysite.co.uk/resources/000/091/259/vicjordancropguide.pdf

GUIDANCE FOR ON-FARM PRACTICE e.g. Opportunities for reducing tillage intensity in conventional arable rotations. Available as part of: AHDB Arable Soil management: Cultivation and crop establishment. https://ahdb.org.uk/arablesoils

RESOURCES

REVIEWS

	First author	Date published	Title	DOI or web-link
R1	Meurer, K.H.E.	2018	Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach	10.1016/j.earscirev.2017.12.015
R2	Haddaway, N. R.	2017	How does tillage intensity affect soil organic carbon? A systematic review	10.1186/s13750-017-0108-9
R3	Cooper, J.	2016	Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis	10.1007/s13593-016-0354-1
R4	Mangalassery, S	2015	Examining the potential for climate change mitigation from zero tillage	10.1017/S0021859614001002
R5	Pittlekow, C. M.	2015	When does no-till yield more? A global meta-analysis	10.1016/j.fcr.2015.07.020
R6	Conant, R. T.	2007	Impacts of periodic tillage on soil C stocks: A synthesis	10.1016/j.still.2006.12.006
R7	West, T. O.	2002	A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States	10.1016/S0167-8809(01)00233-X

EVALUATION IN PRACTICE

	First author	Date published	Title	DOI or web-link
E1	AHDB PR574	2017	Platforms to test and demonstrate sustainable soil management: integration of major UK field experiments	https://ahdb.org.uk/platforms-to-test-and-demonstrate-sustainable-soil-management-integration-of-major-uk-field-experiments
E2	HGCA RR5	1988	Reduced cultivation for cereals	https://ahdb.org.uk/reduced-cultivation-for-cereals
E3	HGCA RR48	2002	Reduced cultivation for cereals: Research, development and advisory needs under changing economic circumstances	https://ahdb.org.uk/reduced-cultivations-for-cereals-research-development-and-advisory-needs-under-changing-economic-circumstances

Description and rating of individual reviews

R1 is a systematic review which builds directly on the work carried out in R2 reviewing of the effect of tillage intensity on soil organic carbon (SOC) by applying an equivalent soil mass approach to account for differences in soil bulk densities. Data were brought together from 101 long-term studies of over 10 years duration.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong	■■■□	■■■□	□□□□	□□□□

R2 is a systematic review of the effect of tillage intensity on soil organic carbon (SOC) in boreo-temperate regions carried out according to the Collaboration for Environmental Evidence systematic review protocol. Data were subject to meta-analysis with consideration of main effects, moderators (depth, climate, soil texture class, initial SOC) and interactions. A total of 351 studies were included in the systematic review.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong	■■■□	■■■□	□□□□	□□□□

R3 is a systematic review bringing together published and un-published data to investigate the impacts of tillage intensity on yield, weed density and soil organic C in organic farming systems for Europe. Data from 41 studies were subject to meta-analysis with consideration of moderators (climate, rotation, soil texture class, management)

Credibility	How it works	Where it works	How to do it	What it costs
Strong	■■□□	■■■□	■□□□	□□□□

R4 is a descriptive review with some data synthesis of soil C storage and yield. Descriptive review includes consideration of direct N_2O and CH_4 fluxes

Credibility	How it works	Where it works	How to do it	What it costs
Moderate	■■□□	■■□□	■□□□	□□□□

R5 is a systematic review of global data assessing the impact of no-till cultivation on yield (including 494 studies with 4842 paired observations in temperate climates). The data richness allowed focussed meta-analysis by crop type, duration of no-till and other management factors.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong	■■■□	■■■□	■□□□	□□□□

R6 is a modelling study coupled to a systematic review to investigate the impacts of occasional tillage (to alleviate compaction or for weed control) in no-till systems on soil C storage. Relatively few data were found that could be used for model evaluation.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong	■■□□	■■□□	■■□□	□□□□

R7 is a synthesis paper using a range of published data sources to create integrated synthesis of all direct and indirect GHG emissions at system scale to compare tillage systems in the USA. Fossil fuel-related emissions are estimated.

Credibility	How it works	Where it works	How to do it	What it costs
Moderate	■■□□	■■□□	■■□□	□□□□

E1 is a synthesis of the findings of several large-plot cultivation experiments in the UK with measurement of the impact of the cultivation systems of soil physical properties potentially affecting root elongation and soil C storage.

UK farm relevance	How it works	Where it works	How to do it	What it costs
Moderate	■■□□	■□□□	■□□□	□□□□

E2 is an early review (1988) of the potential for use of reduced cultivation approaches for cereals with a review of UK plot-based experiments in the 1970 and 1980s; some of the technical information (especially with regard to weed control) is dated but the main soil/cultivation interactions information remains sound including relative energy and labour use in different cultivation systems.

UK farm relevance	How it works	Where it works	How to do it	What it costs
Strong	■■□□	■■■□	■■■□	■□□□

E3 is a review conducted to update E2 and includes wider discussion of practical implementation challenges with farmers and advisers. Specific machinery references are now dated but not obsolete.

UK farm relevance	How it works	Where it works	How to do it	What it costs
Strong	■□□□	■■□□	■■□□	■□□□

7.4. Use of biostimulants

Impact summary

Plant biostimulants are applied at low rates to crops or their rooting zone and contain substance(s) and/or micro-organisms that stimulate natural processes and thereby may enhance/benefit nutrient uptake, nutrient efficiency, tolerance to abiotic stress, and/or crop quality.

Impacts

Reduced net GHG	**+/-**
Other impacts	
Cash crop yields	**+/-**

Cost

	£

How strong is the evidence?

Quality of research and evaluation	**2**
Relevance of context	**2**

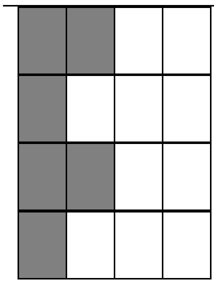
How much is known about?

How it works

Where it works

How to do it

What it costs



This is based on the strongest scores from a number of reviews

Biostimulants - NARRATIVE SUMMARY

What is the intervention?

Biostimulants are currently most used in the horticulture sector, but recommendations for their use are becoming more widespread in the arable sector. According to the definition by the European Biostimulants Industry Council, plant biostimulants contain substance(s) and/or micro-organisms whose function when applied to plants or the rhizosphere is to stimulate natural processes to enhance/benefit nutrient uptake, nutrient efficiency, tolerance to abiotic stress, and crop quality. These materials have no direct action against pests and therefore are not classified as pesticides. There is a wide range of different types of biostimulants, including the following categories identified by the AHDB (2016) biostimulant report: 1) Seaweed extracts; 2) Humic substances; 3) Phosphite and other inorganic salts; 4) Chitin and chitosan derivatives; 5) Anti-transpirants; 6) Protein hydrolysates and free amino acids; 7) Non-essential chemical elements; 8) Complex organic materials; 9) Plant growth promoting bacteria and rhizobacteria; 9) Non-pathogenic fungi; 10) Arbuscular mycorrhizal fungi; and, 11) Protozoa and nematodes. There is also a wide variety of different products within each of these categories, strongly differing in their mechanism of action. The EU Fertilizing Products Regulation (EU 2019/1009) specifies that a plant biostimulant in a product which can demonstrate improvement in one (or more) of four categories: nutrient use efficiency, tolerance to abiotic stress, crop quality traits or availability of nutrients in the soil and rhizosphere. This will define biostimulants by function, rather than composition, and create a requirement for manufacturers to demonstrate to regulators and customers that product claims are justified once the Regulation comes into force in 2022.

There is almost no evidence on the impacts of biostimulants (of any type) on direct GHG emissions. The main mechanism proposed for the potential benefit of the use of biostimulants for GHG emissions is increased crop productivity with the same level of input use (N, fungicide inputs) or maintained productivity with lower inputs.

The following narrative therefore focuses on reviewing evidence that relates to the impacts of biostimulants on the productivity of cash crops .

This narrative summary is based on 1 systematic scientific review of the effects of one class of biostimulants (humic substances, Review 4), 5 descriptive scientific reviews and 1 evaluation in practice that include information relevant to the use of biostimulants in temperate cropping systems. There is some overlap between the primary research studies covered by the systematic/descriptive scientific reviews.

The research-based Evaluation 1 is included as it is the only current study found in the peer-reviewed literature where N_2O emissions have been measured directly in treatments with/ without biostimulants (here two commercial products).

EFFECT on net GHG

How effective is it?

Overall, evidence does not suggest a clear yield response or increased N use efficiency resulting from the use of biostimulants, both positive and negative effects are seen. Hence a similar mixed effect on net GHG emissions is expected.

All reviews that considered the impact of biostimulants on crop growth identify mechanisms can might increase N use efficiency. However, where the existing data are synthesised, this shows a range of impacts, both positive and negative on crop growth; very few studies have considered impacts on yield. All reviews stress that the magnitude and balance of benefits from the use of biostimulants are highly site-specific.

In the one study, single site, two-season, where net GHG emissions were measured, a biostimulant (commercial microbial inoculant) applied together with N fertiliser increased both direct N_2O emissions and indirect N_2O emissions (associated with increased N leaching) with no significant yield benefit.

How strong is the evidence?

Descriptive reviews provide much of the evidence, there is insufficient data available on field evaluation of biostimulants to allow robust data synthesis or meta-analysis of the use of biostimulants (or any class of biostimulants) in UK arable crops. Data syntheses in Reviews 4 and 6 bring together data from some controlled studies but few of these are carried out in the field in temperate climates. Meta-analysis of the impacts of humic substances on early plant growth in Review 5 synthesises findings across a wider range of situations and considers some contextual factors. One research-based field evaluation in temperate conditions of commercial biostimulants on GHG emissions (Evaluation 1) is available.

MECHANISM

How does it work?

Overall the reviews provide a detailed description of the theory underpinning any effects of biostimulants on plant physiology and growth drawn from prior work, largely under controlled laboratory and glasshouse conditions. The reviews provide a comprehensive summary of the interacting mechanisms by which biostimulants can affect plant growth, but all confirm that there have few robustly-evaluated field studies or assessments across the whole crop life-cycle.

WHERE IT WORKS

Overall the reviews provide little information which allow any relevant contextual conditions which determine where/ when biostimulants improve crop yields. All the reviews note the strong site/season specificity of effects. Review 5 identifies some possible factors that could affect agronomic use of humic substances as biostimulants. Review 1 and 4 provide some consideration of the challenges associated with implementation in practice; Review 4 provides a focussed evaluation of the (lack of) evidence to underpin recommendations on rates, timing etc in UK cereal and oilseed crops.

ECONOMIC EVALUATION

The reviews provide no specific information on direct or indirect economic costs and benefits. Review 4 briefly notes that the cost of implementation is low and hence the yield benefit required to offset this expenditure is also low.

The final narrative summary would also include:

FARMER CASE STUDIES - experiences from AHDB Monitor farmers and other practitioners. There have been some tests on Monitor Farms but no case studies are currently available

GUIDANCE FOR ON-FARM PRACTICE e.g. Summary of knowledge of biostimulants for conventional arable rotations. Available at: https://ahdb.org.uk/biostimulants

RESOURCES

REVIEWS

	First author	Date published	Title	DOI or web-link
R1	Jindo, K.	2020	From Lab to Field: Role of Humic Substances Under Open-Field and Greenhouse Conditions as Biostimulant and Biocontrol Agent	10.3389/fpls.2020.00426
R2	Abbott, L. K.	2018	Potential roles of biological amendments for profitable grain production – A review	10.1016/j.agee.2017.12.021
R3	De Pascale, S.	2017	Plant biostimulants: innovative tool for enhancing plant nutrition in organic farming	10.17660/eJHS.2017/82.6.2
R4	AHDB RR89	2016	A review of the function, efficacy and value of biostimulant products available for UK cereals and oilseeds.	https://ahdb.org.uk/a-review-of-the-function-efficacy-and-value-of-biostimulant-products-available-for-uk-cereals-and-oilseeds
R5	Rose, M.T.	2014	A meta-analysis and review of plant-growth response to humic substances: practical implications for agriculture	10.1016/B978-0-12-800138-7.00002-4
R6	Calvo, P.	2014	Agricultural uses of plant biostimulants	10.1007/s11104-014-2131-8

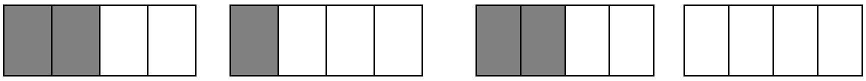
EVALUATION IN PRACTICE

	First author	Date published	Title	DOI or web-link
E1	Souza, E. F. C.	2019	Contrasting effects of inhibitors and biostimulants on agronomic performance and reactive nitrogen losses during irrigated potato production	10.1016/j.fcr.2019.05.001

Description and rating of individual reviews

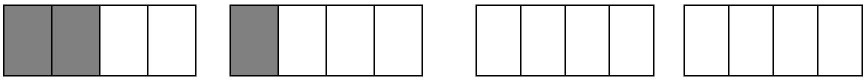
R1 is a descriptive review which considers the mechanisms that may underpin any effect of humic substances on plant growth. It also brings together some considerations on the methods for use for humic substances under field conditions.

Credibility	How it works	Where it works	How to do it	What it costs
Limited quality				



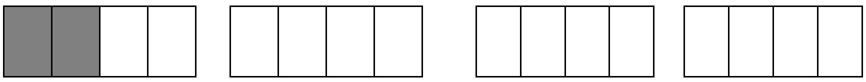
R2 is a descriptive review which considers the current evidence of the effects of biostimulants on plant growth, as well as the effects of a wider range of biological amendments for field crop production. It also brings together considerations of how such diverse amendments should be assessed to provide robust evidence to underpin on-farm decision-making.

Credibility	How it works	Where it works	How to do it	What it costs
Limited quality				



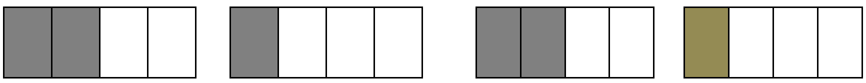
R3 is a descriptive review which considers the mechanisms that may underpin the role of biostimulants in increasing soil nutrient availability, plant nutrient uptake and/or plant nutrient assimilation to provide a scientific framework within which the effects of biostimulants can be assessed.

Credibility	How it works	Where it works	How to do it	What it costs
Limited quality				



R4 is a descriptive review with data synthesis which considers the relative effects of biostimulants of a range of types on above and below-ground growth and overall yield. It also brings together the issues that should be considered where these diverse products are considered for on-farm use for cereals and oilseeds in the UK.

Credibility	How it works	Where it works	How to do it	What it costs
Moderate				



R5 is a meta-analysis of the impacts of humic substances on plant growth (above- and below-ground) for studies in laboratory, glass-house and (few) field conditions mainly conducted during the early growth phase. The data is also used to assess the effects of moderating factors including humic types, rates and growth conditions.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong	■■□□	■■□□	■□□□	□□□□

R6 is a descriptive review with data-synthesis which considers the relative effects of a range of types of biostimulants of on plant growth and nutrient uptake.

Credibility	How it works	Where it works	How to do it	What it costs
Moderate	■■□□	□□□□	□□□□	□□□□

E1 is a peer-reviewed paper reporting the findings of an experiment studying the agronomic and environmental impacts of different inhibitors and two commercial biostimulants in a randomised-complete-block experiment with potatoes

UK farm relevance	How it works	Where it works	How to do it	What it costs
Moderate	■■■□	■□□□	■□□□	□□□□

7.5. Use of organic amendments

Impact summary

Applying organic amendments (livestock manures, biosolids, composts or other materials) to replenish soil fertility or as soil conditioners

Farmyard manure

Impacts

Reduced net GHG	**+**
Other impacts	
Increased soil organic matter	**++**
Increased diffuse N/P losses	**0**
Cash crop yields	**0**

Cost

£££

Livestock slurries; poultry manures

Impacts

Reduced net GHG	**+/-**
Other impacts	
Increased soil organic matter	**+**
Increased diffuse N/P losses	**+/-**
Cash crop yields	**+**

Cost

£££

Biosolids

Impacts

Reduced net GHG	**+/-**
Other impacts	
Increased soil organic matter	**+**
Increased diffuse P losses	**+**
Cash crop yields	**+/-**

Cost

££

Composts

Impacts

Reduced net GHG	**+**
Other impacts	
Increased soil organic matter	**++**
Diffuse N/P losses	**0**
Cash crop yields	**0**

Cost

£££

How strong is the evidence?

Quality of research and evaluation	**4**
Relevance of context	**3**

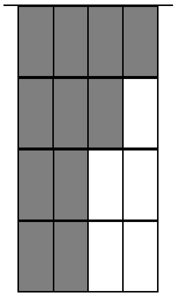
How much is known about?

How it works

Where it works

How to do it

What it costs



This is based on the strongest scores from a number of reviews

Use of organic amendments - NARRATIVE SUMMARY

What is the intervention?

Livestock manures are collected when livestock are housed (often overwinter) and applied as organic amendments to cropland or grazing land to replenish soil fertility. The livestock species and diet together with the method of collection, storage and handling affects the composition of the manures when applied in the field. Liquid manures (with little bedding) are usually referred to as **slurry**; solid manures (where bedding materials are mixed with livestock excreta), except **poultry manures**, are usually referred to as **farmyard manure** (FYM). The fate of livestock manures in soil depends upon the environmental conditions, primarily temperature and precipitation, as well as the method and timing of application. The use of livestock manures on arable crops is common on mixed farms, but organic manures may be also be purchased for use on arable farms or applied as a result of a reciprocal straw-for-muck deal with a livestock farmer.

Biosolids are organic materials produced during wastewater treatment at sewage treatment works. A number of processes may be used during sludge stabilisation such as anaerobic digestion, screening, dewatering and, in some instances, composting. The UK Government has a clear strategy for beneficial recycling of biosolids in preference to other forms of disposal e.g. by incineration or landfill, and c. 87% of sewage sludge is currently recycled as biosolids to agricultural land. The Sludge (Use in Agriculture) Regulations 1989 govern the use of Biosolids and requires: 1) soil to be analysed for heavy metals before biosolids can be spread for the first time, and; 2) there are steps in place to ensure that soil heavy metal concentrations are kept below defined limits. Potential risks from pathogens when biosolids are spread on land are addressed by guidance within The Safe Sludge Matrix 2001; there are no restrictions when applications are made to crops of cereals or oilseed rape. Biosolids contain a relatively high proportion of phosphate compared with other sources of organic materials. Biosolids are commonly spread by contractors.

Composting is the biodegradation of organic materials through a self-heating, solid phase, aerobic process. This converts the organic materials into a stable product known as **compost**. The initial decomposition phases break down available sugars and celluloses and then lignins are also broken down (dominantly by fungi); stabilisation of the compost occurs during the final maturation phase. Organic waste materials produced in households include kitchen and garden wastes; these wastes are increasingly collected separately as part of kerbside waste collection. In addition, organic waste materials are produced during food processing at catering and industrial scales, green wastes are produced in the amenity and forestry sectors and industrial processes such as paper making /recycling also produce organic wastes. Some of these wastes may be made available for agricultural use without further treatment (e.g. paper crumble), but many are first composted. Production of compost in the UK is assured by the Compost Certification Scheme to the BSI PAS100 standard. Compost produced in this way is considered a product and is not subject to the need for an environmental permit before application, some other organic wastes have an exemption (U10), but for other industrial wastes, environmental permits are likely to be required. The sources of organic materials together with the method of collection, storage and handling affects the composition when applied in the field.

The following narrative focuses on reviewing evidence that relates to the changes in C storage in soils in cropping systems where organic amendments are applied and direct GHG emissions (focussed on N_2O). The use of organic amendments is broken down by type in the associated summaries. However, the under-pinning evidence base is often cross-cutting and hence it is brought together in a single narrative summary.

A range of other impacts of organic amendments are noted in these reviews and hence are summarised briefly in the narrative summary. The use of livestock manures in cropping systems for crop nutrient supply has been common practice for centuries and the dependence of cropping systems on the recycling of nutrients through organic amendments was only broken with the development of mineral fertilisers.

This narrative summary is based on 5 systematic/descriptive scientific reviews and 2 evaluations in practice that include information relevant to the impact of organic amendments on net GHG in temperate cropping systems.

All reviews build from the long-established understanding of the carbon cycle in soils and the factors affecting soil organic matter content as given in textbooks. A good summary, with reference to long-term UK data, is given by Johnston et al. (2009, *Advances in Agronomy 101: 1-57, doi:10.1016/S0065-2113(08)00801-8*). There is some overlap between the primary research studies covered by the systematic/descriptive scientific reviews, and in some cases, later reviews deliberately build on the findings of the earlier published work.

EFFECT on net GHG

How effective is it?

Overall, evidence tends to show a mixed effect where the impact on net GHG depends on the composition of the organic amendment, how it is used in conjunction with N fertiliser and how close soils are to their attainable C storage levels (largely determined by climate and soil types.

For arable soils in the UK, we assume that soils are well below this maximum and hence these soils have a high capacity to increase C storage over the medium-term (10-25 years).

Direct N_2O emissions are always higher on heavy soils.

How strong is the evidence?

High quality systematic reviews and meta-analysis underpin much of the evidence, though often focussing on aspects of the GHG balance where organic amendments are used alongside or in place of fertiliser (Reviews 1, 2, 3, 5). Differences in organic amendment types, climates and soil types were able to be taken into account in the analysis in several reviews.

Some assumptions and conversion factors are needed to take measured data e.g. of fertiliser N replacement or soil C storage and express these in terms of GHG emissions. These are based on agreed IPCC conversion factors.

MECHANISM

How does it work?

Overall the reviews provide a full description of the theory of change drawn from prior work and testable predictions generated from it. Reviews 1 and 5 specifically address the question of whether changes in soil organic matter content as a result of the use of organic amendments provide a net GHG benefit. Reviews 2 and 3 provide a comprehensive summary of the interacting mechanisms by which introducing organic amendments to cropping systems leads to changes in direct N_2O emissions. E1 puts these processes into a clear UK agronomic context.

All reviews confirmed that the regular application of livestock manures, composts and other organic amendments to land increases soil organic matter compared with soils not receiving manures, if this additional C is able to be stabilised biochemically or biophysically within the soil. Organic amendments contain 40–60% C on a dry weight basis and therefore provide inputs of carbon to the soil. The total amount of C in the soil is a balance between all the C inputs (e.g. from litter, residues, roots, as well as any organic amendments) and C losses (mostly through soil respiration, increased by soil disturbance). On average, arable soils have C contents that are lower than the attainable C storage levels (largely determined by climate and soil type). Therefore, within a given soil and climatic regime, a linear relationship commonly exists between C inputs and changes in soil organic matter for arable soils. E2 showed that soil organic matter stocks (t/ha) were increased by 7% for each 10 t /ha addition of organic C in amendments irrespective of amendment or soil type. In general, greater increases are seen with stacked and composted manures at typical field application rates than with slurries, because lower inputs of C on a dry weight basis are usually made in slurries.

However, R1 and R5 identify that such an increase in soil organic matter does not necessarily deliver a reduction in net GHG through soil carbon storage (when assessed at landscape rather than farm scale) Adding organic materials such as animal manure to soil, whilst increasing soil organic matter, generally does not constitute an additional transfer of C from the atmosphere to land. However, application of manures to arable land with low soil organic matter levels, if transport distances are low, is likely to have a greater benefit than application to grassland or other systems with soil organic matter levels close to the system's equilibrium maximum attainable C storage level.

Once applied to soil, organic amendments are further decomposed by soil micro-organisms; this can enhance microbial abundance and diversity and promote soil health by improving soil aggregation and aggregate stability, thereby increasing aeration and workability. E1 quantifies the impacts of organic amendments on a range of other soil properties.

Organic amendments may release significant amounts of plant-available nutrients (N, P, S) through mineralisation depending on the composition of the materials, and often act as a slow-release fertiliser throughout the growing season replacing the need for other mineral fertilisers, as shown by E1. Any replacement of fertiliser N with N from organic materials is likely to result in a net reduction of GHG. However, as discussed more fully by R4 there are also emissions, direct and indirect, from the application process (e.g. fuel used for transport, spreading) and these will partly offset the savings.

E1 and E2 compare the effects of different organic amendment types on crop yield and soil properties. Organic amendments vary in:

- Dry matter content. By definition, slurries have a high water content in comparison with stacked or composted manures, but the dry matter content of different slurries can also vary greatly. This affects the amount of C added to soil

- Content of readily-available water-soluble C and nitrogen (ammonium, nitrate, urea, uric acid). Poultry manures and slurries usually contain greater concentrations of readily available nutrients than composts and hence have a larger fertiliser replacement value.

- Decomposability. High-quality organic amendments with a low carbon to nitrogen ratio (C:N) decompose quickly, mineralising N into available forms but contribute less to stable organic matter in the soil, whereas amendments with a high C:N (low quality) decompose slowly and therefore may not supply sufficient N to meet crop demand, potentially resulting in lower yields.

R2 and R3 specifically consider the Impacts of organic amendments on N_2O emissions and show that this depend on a number of interacting factors directly linked to their composition:

- organic N must be mineralised before becoming susceptible to loss, hence at the same overall N application rate, N_2O losses from slowly-decomposing organic amendments may be lower than for mineral fertilisers;

- organic amendments with high water contents such as slurries saturate soil micropores in the short-term and can stimulate N_2O losses immediately following application;

- increases in water-soluble and other labile carbon stimulate microbial activity and may increase nitrification and denitrification processes, if soil contents of ammonium and nitrate are high, contributing to higher overall N_2O emissions.

WHERE IT WORKS

Overall the reviews provide a theoretically grounded description of relevant contextual conditions which determine where/ when organic amendments affect net GHG. Although there is a long-standing body of evidence on the use of organic amendments in the context of crop nutrient supply. There is much less documentation of the challenges associated with the integration of organic amendments in arable cropping systems where they have not been used for a long time. Risks of increasing net GHG as a result of increases in N_2O emissions are higher on heavy soils.

The key factors determining the impact of organic amendments largely relate to the composition of the amendments. Organic amendments with high fertiliser replacement value must be managed carefully in terms of timing and rate of application to limit the risk of increasing N_2O emissions; they also commonly have only a small positive impact on soil C storage.

Composted amendments and farmyard manure have a positive impact on soil C storage for UK arable soils but have only a low fertiliser replacement value.

ECONOMIC EVALUATION

Overall the reviews, provide limited information on direct or indirect economic costs and benefits.

The final narrative summary would also include:

FARMER CASE STUDIES - experiences from AHDB Monitor farmers and other practitioners.

Case studies developed for Defra as part of the KeySoil project could be refreshed- http://www.keysoil.com/

GUIDANCE FOR ON-FARM PRACTICE e.g.. Measuring and managing soil organic matter. Available at: https://ahdb.org.uk/knowledge-library/measuring-and-managing-soil-organic-matter

Resources

REVIEWS

	First author	Date published	Title	DOI or web-link
R1	Sykes, A. J.	2020	Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology	10.1111/gcb.14844
R2	Charles, A.	2017	Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis	10.1016/j.agee.2016.11.021
R3	Graham, R. F.	2017	Comparison of organic and integrated nutrient management strategies for reducing soil N2O emissions	10.3390/su9040510
R4	Johnson, J. M-F	2007	Agricultural opportunities to mitigate greenhouse gas emissions	10.1016/j.envpol.2007.06.030
R5	Powlson, D. S.	2011	Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false	10.1111/j.1365-2389.2010.01342.x

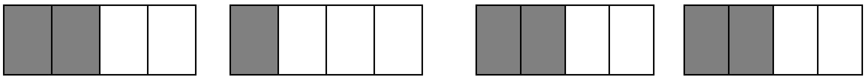
EVALUATION IN PRACTICE

	First author	Date published	Title	DOI or web-link
E1	WRAP	2016	Digestate and Compost in Agriculture (DC-Agri)	http://www.wrap.org.uk/content/digestate-and-compost-agriculture-dc-agri
E2	Bhogal, A.	2011	Effects of recent and accumulated livestock manure carbon additions on soil fertility and quality	https://doi.org/10.1111/j.1365-2389.2010.01319.x

Description and rating of individual reviews

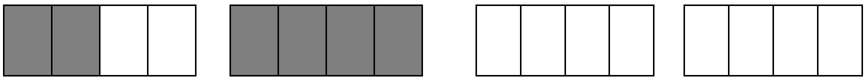
R1 is a descriptive review which draws on the best available evidence to compile a critical integrative review of options to increase soil C storage. The use of organic amendments is discussed in terms of feasibility and impacts and compared with a range of other options within a clear and consistent framework.

Credibility	How it works	Where it works	How to do it	What it costs
Strong				



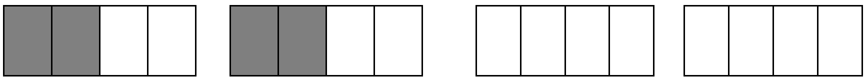
R2 is a systematic review of the N2O emission factors of soils in a range of agricultural systems receiving organic amendments; 93% of the data were from temperate systems. Data were subject to meta-analysis with 38 studies and 422 observations included within the systematic review. Context factors explored in analysis included the composition of the amendments and whether mineral N fertilisers were used together with the amendments, soil and climate factors.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong				



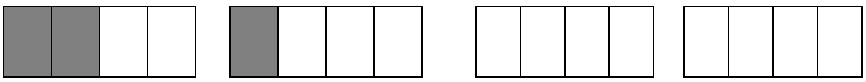
R3 is a systematic review of the N2O emissions for no N fertiliser, mineral N fertiliser, organic N inputs vs. combined mineral and organic fertilisation with a consideration of impacts on crop yield; limited data were found to fit the rigorous comparison criteria but these detailed studies allowed critical assessment of the controlling factors as well as overall differences between the management approaches.

Credibility	How it works	Where it works	How to do it	What it costs
Very strong				



R4 is a descriptive review which considers opportunities to mitigate GHG in agricultural systems and summarises the literature to date (2007) on the impacts of application of livestock manures on soil C storage and the importance of full C accounting.

Credibility	How it works	Where it works	How to do it	What it costs
Moderate				



R5 is a descriptive review which critically examines the principles determining whether changes in soil C storage contribute to net GHG reductions examining the extent to which changes in soil C storage may represent changes in the form/location of C storage rather than an additional transfer of C from the atmosphere to land. The addition of organic amendments is specifically considered.

Credibility	How it works	Where it works	How to do it	What it costs
Strong	■■■□	□□□□	□□□□	□□□□

E1 is the summary report from a series of research studies carried out over the medium-long-term in the UK on the use of organic amendments; field measures included N2O emissions and leaching as well as impacts on N supply for crops, yield and soil organic matter.

UK farm relevance	How it works	Where it works	How to do it	What it costs
Moderate	■■■□	■■■□	■□□□	■□□□

E2 is a synthesis of some of the findings of the experimental series reported in E1 with a focus on the impact of organic amendments on soil organic matter and soil fertility across all sites .

UK farm relevance	How it works	Where it works	How to do it	What it costs
Moderate	■■■□	■□□□	■□□□	□□□□