Regenerative Agriculture in Cropping Systems: Knowledge gaps, research needs and how to address them

Challenge 5 (of 6): Wider System Considerations

Julia Cooper
Organic Research Centre

Elizabeth Stockdale
NIAB

Belinda Clarke
Agritech E

Contents

Thank You 01

Background/Introduction 02

Key Findings 04

Challenge 5: Wider system considerations

5.1 Impacts of regenerative agriculture systems on the water cycle (flood risk, drought resilience) 05

5.2 Impacts of integration of legumes throughout the cropping system on N cycling including greenhouse gas emissions 09

5.3 Practices and options for regenerative agriculture to be assessed in terms of wider impacts (e.g. whole life cycle analysis for input options) 13

5.4 The impact of regenerative agriculture on product quality and end-market use 18

5.5 Impacts of regenerative agriculture on food quality, particularly nutrient density 20

Project Summary 23

Authors' Recommendations 27

Appendix A 30

Bibliography 29

Thank You

The authors would like to thank Aurora Trust, The Mark Leonard Trust and the Gatsby Charitable Foundation for their generous funding to produce this report.

Introduction

Although the term regenerative agriculture was coined in the late 1980s, the term was not widely used in the agricultural or scientific community until the late 2000s. Since then the term 'regen ag' has become commonplace in UK agriculture. Although much emphasis has been placed on the adoption of key principles by farmers, this has not always been supported by scientific knowledge and understanding. This series of reports was commissioned to provide a quick overview of the state of knowledge and research activity on a number of topics important for the development of regenerative agriculture in the UK, with a particular emphasis on priorities for farmers. The goal was to prioritise research topics and identify where the current gaps in knowledge exist so that future funding can be targeted towards topics that have previously been insufficiently studied.

This report was produced as a result of a Rapid Evidence Assessment (REA).
To conduct this REA a list of research priorities was drafted based on informal conversations with key stakeholders and reviews of prior research prioritisation exercises. In addition an online workshop with stakeholders (19 in total) was used to rank the priorities and discuss best approaches to conduct the research. This was followed by a detailed scoping study of ongoing and past projects in the UK which were mapped to the list of research priorities. In parallel, searches of published academic literature were conducted and a selection of papers on each topic were rapidly reviewed and synthesised.

The results were briefly presented at the Cambridge Future of Agriculture Conference (held in March 2024), which served as a unique platform for farmers, farmer organisation representatives, and scientists to openly discuss and shape future research needs; these are reflected in this report.

It is important to keep in mind that this study was not done in isolation. There have been several reviews on similar topics conducted in the past few years. These include the rapid evidence review by Albanito et al (2022) (1) that was commissioned by the Committee on Climate Change to assess the role of agroecological farming in the UK transition to Net Zero; the DEFRA-commissioned study on the impacts of agroecological compared to conventional farming systems published by Burgess et al (2023) (2); and most recently, the assessment of farmer priorities for research conducted by the Agricultural Universities Council. Regenerative systems and carbon sequestration have been identified through that process as new priorities while soil health and crop breeding have persisted from previous assessments.

This project focused specifically on challenges relating to implementing regenerative agriculture in cropping systems, with a particular emphasis on soil health. This makes it slightly more focused than these other studies and the information gathered complements the outcomes of these three recent studies.

1. https://www.theccc.org.uk/publication/agroecology-a-rapid-evidence-review-university-of-aberdeen/
2. See all three reports from: Evaluating the productivity, environmental sustainability and wider impacts of agroecological compared to conventional farming systems project SCF0321 for DEFRA. 20 February 2023

Key Findings

Detailed summaries of the outcomes of the survey and discussion during the workshop along with the knowledge gaps listed above, were synthesised into 6 challenges and 34 sub-challenges. Because of the diverse topics and range of study types identified in the peer-reviewed literature, a narrative synthesis approach was used to summarise the findings for each topic. This focussed on descriptive (rather than numerical) summaries of the findings highlighting themes where the research results appeared to converge or diverge.

The six challenge areas identified were:

1. Standardisation of regenerative agriculture
2. Advice and Guidance or "How to…"
3. Crop genetic resources
4. Soil health
5. Wider system considerations
6. Socio-economics

This publication presents the findings of Challenge 5: Wider Systems Considerations.
The findings of the other challenges can be found in the associated series of publications available at www.organicresearchcentre.com.

5.1 Impacts of regenerative agriculture systems on the water cycle (flood risk, drought resilience)

Compilation of evidence on the wider system impacts of regenerative agriculture is particularly interesting to government policy makers. The UK Department of Environment, Food and Rural Affairs in the new Labour Government is currently reviewing policies relating to farming and land management in the context of the Environmental Improvement Plan (EIP) (3). This plan sets out 10 goals, several of which are relevant to the agricultural sector. New farming schemes is listed in the plan as one of the tools that will be used to deliver environmental targets. Key aspects of the delivery plan include supporting landowners and farmers to adopt nature friendly farming, reducing ammonia emissions and N, P and sediment pollution of water, promoting safe use of pesticides and IPM, and a clear commitment to building soil health, including developing an indicator and baselining soils. Using land management to adapt to and mitigate climate change is key, particularly through nature-based solutions that mitigate flood risk. All of these initiatives can be delivered through changes to farming practice, but the evidence base is needed to support policy.

3. https://www.gov.uk/government/publications/environmental-improvement-plan

A key component of Goal 7 of the EIP is mitigating and adapting to climate change, including mitigation of flood risk. Regenerative agriculture is a system which should deliver benefits to the water cycle through improvements in soil health that improve infiltration and water holding capacity and the maintenance of residues and growing crops in the landscape which reduce runoff and also improve infiltration. However, not all evidence supports the assumption that regenerative agriculture will positively affect the water cycle.

Farming practices that increase residues on the soil surface can reduce runoff and promote infiltration, but only when soil is well aggregated and not compacted. Reduced tillage intensity i.e. minimum or no-till systems, can also increase runoff if no-till practices lead to compaction (Albanito et al. 2022).
There are a number of peer-reviewed studies which discuss the water cycle in the context of regenerative farming. Twenty-four of these are review articles which were rapidly screened for this analysis; only three of these were relevant to the UK and these are discussed below.

In rotations, the integration of ley phases, a key component of many regenerative arable rotations, improves a variety of soil physical properties (Cooledge et al. 2022). Berdeni et al. (2021) used soils extracted from different management systems (arable, permanent grass, grass-clover ley) at Leeds University farm and exposed them to ambient, drought and flood conditions. They provided clear evidence that the ley phase of the rotation was key to improving soil hydrology, including infiltration rates, macropore flow and saturated hydraulic conductivity, as well as reducing compaction. They reported that wheat yields were improved by 42-95% under flood and ambient conditions in the ley soils. Much of the hydrological improvement was attributed to enhanced earthworm activity in ley soils. In the publication they advocated strongly for introduction of more leys into arable rotations, arguing that “leys will help to deliver reduced flood and water pollution risks, potentially justifying payments for these ecosystem services”.

The potential benefits of regenerative farming practices for catchment scale hydrology have been modelled. Liu et al. (2023) simulated the water cycle and flood risk in Norfolk using a catchment-scale model and tested the effects of nature-based solutions, including implementation of regenerative farming on agricultural land. They modelled impacts of regenerative farming by adjusting model parameters, specifically field capacity, which was increased to 0.4 so that more water was retained in the soil and less discharged through surface runoff. On this basis, the model predicted a lower risk of floods, but the increase in water retention also meant that less water was available for groundwater recharge. This illustrates the sometimes-unexpected offsite effects of changes in farming practice. In this case, the authors pointed out that higher levels of available water in the soil may improve crop growth, so this is a tradeoff that may be desirable depending on the relative demand for irrigation water versus household drinking water.

In contrast, a modelling study by Collins et al. (2023) did not find that the introduction of regenerative farming practices to a catchment in the Cotswold Hills significantly reduced flooding relative to standard farming practice. In this study the conventional rotation was assumed to be winter wheat-winter oilseed rape compared with a regenerative rotation of four years arable crops (winter wheat, winter oilseed rape, broad beans, spring barley) followed by a four-year herbal ley. The modellers used the below-ground soil properties of a permanent grass to represent the improved hydraulic properties from regen ag. But in this case, the catchment was highly permeable and flooding was primarily a function of the groundwater level and not surface runoff, so that the type of cropping system (conventional or regenerative) had minimal impact on the flood risk.

This suggests that the hydrology of the catchment and dominant factors contributing to flooding need to be taken into account before concluding that regenerative agriculture should be promoted as part of natural flood management.

The potential for regenerative agriculture practices to reduce the risk of drought is well documented. Many of the practices used in regenerative agriculture emerged from the conservation agriculture movement, which had protection of soil from erosion by wind or water and retention of moisture in soils as key objectives. Albanito et al. (2022) conducted a detailed review of many agroecological farming practices, including reduced soil disturbance and diverse crop rotations. They reported that cover crops can increase water holding capacity, soil porosity and aggregate stability – all of which would reduce risks from droughts. But a negative impact of cover crops could be increased transpiration, which can result in reductions in groundwater recharge (Burgess et al. 2023). This suggests that while regenerative practices may improve water relations for crops, there may be wider impacts on the water cycle (e.g. reduced groundwater recharge) that need to be taken into consideration before making policy recommendations.

While carbon emissions and biodiversity loss are a key focus of government policy at the landscape scale, managing the water cycle to ensure safe and sufficient water supplies and to mitigate risks of drought and flooding, are also priorities. However there has been much less focus on the impacts of regenerative agriculture systems on the water cycle at field, farm and catchment scale. Regenerative agriculture has been identified as a system conducive to natural flood management at the catchment scale. It is also being promoted as a way to mitigate risk from weather extremes that cause drought. This high-priority area for applied research will require multidisciplinary studies involving environmental modelers and policymakers. Scenarios explored should be co-developed with farmers to ensure realism.

5.2 Impacts of integration of legumes throughout the cropping system on N cycling including greenhouse gas emissions

Legumes can be integrated into cropping systems in a variety of ways that may affect GHG emissions through various direct and indirect mechanisms. Nitrogen-fixing break crops in rotations are promoted as part of the government's EIP and will address Goal 2 (Clean air), Goal 6 (Using resources from nature sustainably) and Goal 7 (Mitigating and adapting to climate change). The Sustainable Farming Incentive's legume fallow (NUM3) and herbal ley (SAM3) options allow a break from arable cropping and include N fixing forage legumes. Various multi-species cover crop options (Multi-species winter cover: SAM2, Multi-species spring-sown cover: SOH2, Multi-species summer-sown cover: SOH3) may include a legume for a shorter period within the rotation. Grain legumes, including pulses, can also be integrated into regenerative arable rotations as break crops between cereals or as intercrops (see Challenge 2.2). Living mulch systems (see Challenge 2.4) also normally include a perennial legume cover.

The effects of legumes in diverse rotations on greenhouse gas emissions has been covered extensively in peer-reviewed literature; 58 review articles were rapidly screened to extract key information relevant to the UK.

These practices can impact GHG emissions and the systems' carbon footprint in various ways and are often included in descriptions of "climate-smart agriculture" (CSA) with the assumption that integrating legumes into cropping systems has a net positive effect on GHG emissions (Erekalo et al. 2024). Cooledge et al. (2022) provide a comprehensive review of the importance of herb- and legume-rich multispecies leys in arable rotations, focusing on the UK context. Many of the benefits they highlight come from legumes in the ley mixtures fixing nitrogen, which reduces the need for nitrogen fertilizer during the growing season and build up soil nitrogen reserves, lowering the nitrogen requirements of future crops in the rotation. Grass-clover leys in an arable rotation can save 50-75% of the N fertiliser typically applied to the arable crops

(Cooledge et al. 2022). Manufacture of N fertiliser results in an average carbon footprint of 2.6 kg CO_2e/kg N, so reductions in its use reduce off-site emissions. There are some risks: ley phases in rotations can result in emissions of GHG following termination, especially if they are ploughed. Nitrate can leach into watercourses and be lost to the atmosphere through denitrification (Cooledge et al. 2022). This risk was also highlighted by Hansen et al. (2019) in a review of organic farming and sources of nitrous oxide emissions.

Increases in the area of grain legumes is increasingly proposed as an agroecological/regenerative strategy linked to reductions in animal protein consumption and reductions in the carbon footprint of the food system. Prof Bob Rees and colleagues at the Scottish Rural University College (SRUC) have studied strategies to mitigate climate change in agriculture extensively; they identified increased cultivation of grain legumes as the single most effective emission mitigation measure applicable to agricultural land in a report for Scotland's centre of expertise on climate change (Eory et al. 2020). Burgess et al. (2023) included integration of legumes into crop rotations in their evaluation of agroecological practices for Defra in 2023.They confirmed that inclusion of a legume crop in a cereal rotation can reduce GHG emissions; although they reported that evidence for this is still "incomplete". Albanito et al. (2022) also assessed the quantity and quality of evidence for GHG impacts of including grain legumes in arable rotations; they reported that the evidence was "weak" for a positive effect of this practice. This suggests that there is scope for more fundamental research on the GHG implications of integrating more grain legumes into rotations, on both direct and indirect emissions.

Legumes can also impact rates of soil C sequestration, thus indirectly affecting a farming system's carbon footprint. Cooledge et al. (2022) report that including legumes in ley phases increases soil organic carbon more than grass-only leys, suggesting that the legumes impact carbon accumulation rates in soils and its persistence. Singh et al. (2023) describe various mechanisms by which legumes can promote soil C sequestration, including deep root systems, increased release of root exudates, and higher levels of leaf deposition. They also cite a paper by Six et al. (2002) which explains that rotations that include legumes promote more accumulation of carbon in macroaggregates, which is linked to C sequestration.

The past projects listed in Table 1 will provide useful background information on the impacts of legumes within regenerative rotations on GHG emissions. The ongoing projects in Table 2 are also a good source of background information and context for this area of work. Organisations and researchers involved in these should be contacted for input into design of future programmes in this area

Integration of legumes into crop rotations is proposed as a regenerative practice that will reduce the need for N fertilisers, but legumes also emit GHG during the fixation process and after incorporation of their residues into the soil. Various studies have been done in the UK to refine the emission factors associated with legumes grown in the field (see work by Bob Rees and his team at Scotland's Rural University College) but further studies on tradeoffs between different cropping systems are needed. This is a high priority for applied research. In addition, modelling studies building on the work of the Food, Farming and Countryside Commission's Farming for Change report should be conducted to better understand the implications of a higher proportion of UK-grown legumes on GHG emissions, diets and the livestock sector.

Table 1 Summary of past projects with relevance to the topic of GHG emissions from legumes in regenerative agriculture

Title	Lead Organisation	Date	Study type
Utilising N in cover crops - NT2302	RSK ADAS Ltd	1999	synthesis
The contribution of cover crops incorporated in different years to nitrogen mineralisation - NT1526	RSK ADAS Ltd	1999	experiment
Optimisation of nitrogen mineralisation from winter cover crops and utilisation by subsequent crops. - OF0118T	Horticulture Research International/Henry Doubleday Research Association	2000	experiment
Agriculture and climate change: turning results into practical action to reduce greenhouse gas emissions - A review - AC0206	IGER	2007	review
Beans and wheat intercropping: a new look at an overlooked benefit	Organic Research Centre	2013	experiment
Bi-cropping spring field bean and wheat for UK wholecrop forage production	RAU	2015	experiment
A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species	AHDB	2016	review
Cover, catch and companion crops. Benefits, challenges and economics for UK growers.	Game and Wildlife Conservation Trust	2017	experiment
Agroecology - a Rapid Evidence Review (for the Committee on Climate Change)	University of Aberdeen	2022	synthesis
Evaluating agroecological farming practices – SCF0321	Cranfield University	2023	review

Table 2 Ongoing projects in the UK with relevance to integrating legumes into regenerative cropping systems

Name (funder where information is available)	Lead Organisation	Website
The Allerton Project	Game & Wildlife Conservation Trust	https://www.allertontrust.org.uk/
Fix Our Food (Transforming UK Food System, Strategic Priorities Fund Programme, UKRI)	York University	https://fixourfood.org/
Quantifying the Potential for Regenerative Agriculture to Contribute to Net-Zero in the UK (AgriFood4NetZero, UKRI)	University of Leeds	https://www.agrifood4netzero.net/2023-funded-scoping-studies.html
Leguminose (Horizon Europe, UKRI)	Reading University	https://www.leguminose.eu/the-project/
Sustainability Trial for Arable Rotations (Felix Thornley Cobbold Agricultural Trust, The Morley Agricultural Foundation)	NIAB	https://www.niab.com/research/agronomy-and-farming-systems/research-projects-agronomy-farming-systems/sustainability
Centre for High Carbon Capture	NIAB	https://www.niab.com/research/agronomy-and-farming-systems/centre-high-carbon-capture-cropping
Large-scale Rotation Experiment (various including Lawes Agricultural Trust, BBSRC, H2020, HEurope)	Rothamsted Research	https://www.rothamsted.ac.uk/news/new-long-term-experiments-rothamsted-will-shed-light-potential-impacts-regenerative

5.3 Practices and options for regenerative agriculture to be assessed in terms of wider impacts (e.g. whole life cycle analysis for input options)

In addition to effects on the water cycle (section 5.1) and the specific effects of legumes on GHG emissions (section 5.2) regenerative agriculture may have a wide range of other direct and indirect effects on a range of environmental and societal outcomes. Life cycle analysis methods are commonly used to assess these impacts, very often from the perspective of a single product. These include standard LCA which may include only the common environmental indicators of impact e.g. global warming potential, fossil energy use, marine and freshwater eutrophication, freshwater acidification and water scarcity (Weiner et al. 2024) and Social LCA (S-LCA) which can cover a range of indicators linked to human health and well-being e.g. workers' conditions, equality, safety, life expectancy, fair wages etc (Ramos Huarachi et al. 2020). More advanced modelling approaches would be needed to expand this sort of analysis to include the impacts of a change in the farming system on the landscape and wider societal scale. Some evidence reviews also provide a good overview of these wider impacts.

Peer-reviewed literature that uses S-LCA to explore the social implications of a change to regenerative farming systems is non-existent. Environmental LCAs featuring regen ag are also not common, although many of the practices characteristic of regenerative agriculture have been assessed (e.g. see (Weiner et al. 2024) who discuss integration of grain legumes into rotations).

Rehberger et al. (2023) consider the evidence that regenerative agriculture (or practices common to regen ag) can build soil organic carbon and conclude that there is a wide variation in effects, finally arriving at a figure of 0.3 t C/ha/yr accumulated in no-till systems, with some increases in systems with cover crops, and cover cropping with perennials in rotation resulting in the highest rates of C accumulation. But as with all studies on soil carbon dynamics, outcomes are very context-specific needing to take account of soil carbon levels at the beginning of the conversion to regen ag practices, as well as the number of practices implemented together, external inputs of carbon, and local soil and environmental conditions. These factors make it very difficult to use global evidence reviews and meta-analyses to draw a conclusion about how regen ag might affect soil carbon levels in UK farming systems. In fact, Burgess et al. (2023) identified a gap in evidence for the effects of cover crops on soil carbon under UK conditions, confirming the need for more local evidence to help formulate policy and advice.

The same evidence review (Rehberger et al. 2023) also touches on the effects of regen ag on biodiversity, drawing on global studies that have documented improvements from regen ag practices. Tamburini et al. (2020) synthesised results (using a second-order meta-analysis method) from thousands of studies on agricultural diversification and reported very positive impacts on biodiversity, pollination, pest control, nutrient cycling, soil fertility and water regulation for practices commonly used in regen ag, e.g. reduced tillage, organic amendment, and crop diversification in the field. This study demonstrates the pattern of effects globally for these practices, but there is still a need for more UK-specific evidence of how specific practices implemented within UK farming systems impact biodiversity.

The studies by Burgess et al. (2023) and Albanito et al. (2022) reviewed evidence to make recommendations to Defra and the Committee on Climate Change, respectively, on the potential of regenerative and agroecological farming to address productivity, environmental and climate mitigation targets in the UK. Most of the practices explored (e.g. crop rotations, conservation agriculture/reduced soil disturbance, cover crops) increase soil and/or biomass carbon and biodiversity. However, for other outcomes (yields, input costs, GHG emissions) there are more variations in the results depending on the specific practice and the baseline comparison. Specifically, Albanito et al. (2022) reported increases in emissions of the potent GHG nitrous oxide when practices like no-till, retention of straw, use of organic manure and cover crops are implemented. But they also explained that there are significant gaps in knowledge about the net effect of adopting a selection of regen ag practices on GHG emissions.

The studies by Burgess et al. (2023) and Albanito et al. (2022) highlight the trade-offs between the implementation of specific practices and outcomes at the farm scale. This is further complicated by the need to assess knock-on impacts of changes in farm practice beyond the farm gate. Projects like Fix our Food (4) and H3 (Healthy Soil, Food, People) (5) are exploring the impacts of transitioning to a regenerative farming system on wider society and should provide useful experience and outputs to inform future research in this area.

Burgess et al. (2023) provide a valuable deep dive into the various ways that modelling could be used to simulate an agroecological/regenerative future. They point out that the complexity of scales involved (farm, landscape, national) and systems (agricultural or whole food system), as well as outcomes of interest (productivity, environmental, societal) imply that no one modelling approach will be appropriate. Instead, they suggest that a "modelling framework" approach is adopted that consists of "a suite of models applied for a common purpose using common input data." The full report provides onsiderable detail on the different models that could be used to model the impacts of agroecological/regenerative farming systems relative to business-as-usual farming. It also highlights the need for collation of available data on the impacts of specific regenerative (agroecological) farming practices using data from experiments, targeted networks and existing national networks. The purposes of these different scales of monitoring are illustrated in Figure 1 overleaf.

A related project commissioned by the Food Farming and Countryside Commission (FFCC) modelled the impacts of a transition to agroecological farming in the UK by 2050 (Poux et al. 2021). The agroecological methods used in the exercise were similar to organic farming, so they were not strictly regenerative, and assumptions about

4. https://fixourfood.org/

5. https://h3.ac.uk/

Figure 1 Detailed illustration of three levels of monitoring networks for agroecology/regenerative agriculture copied from Burgess et al. (2023)

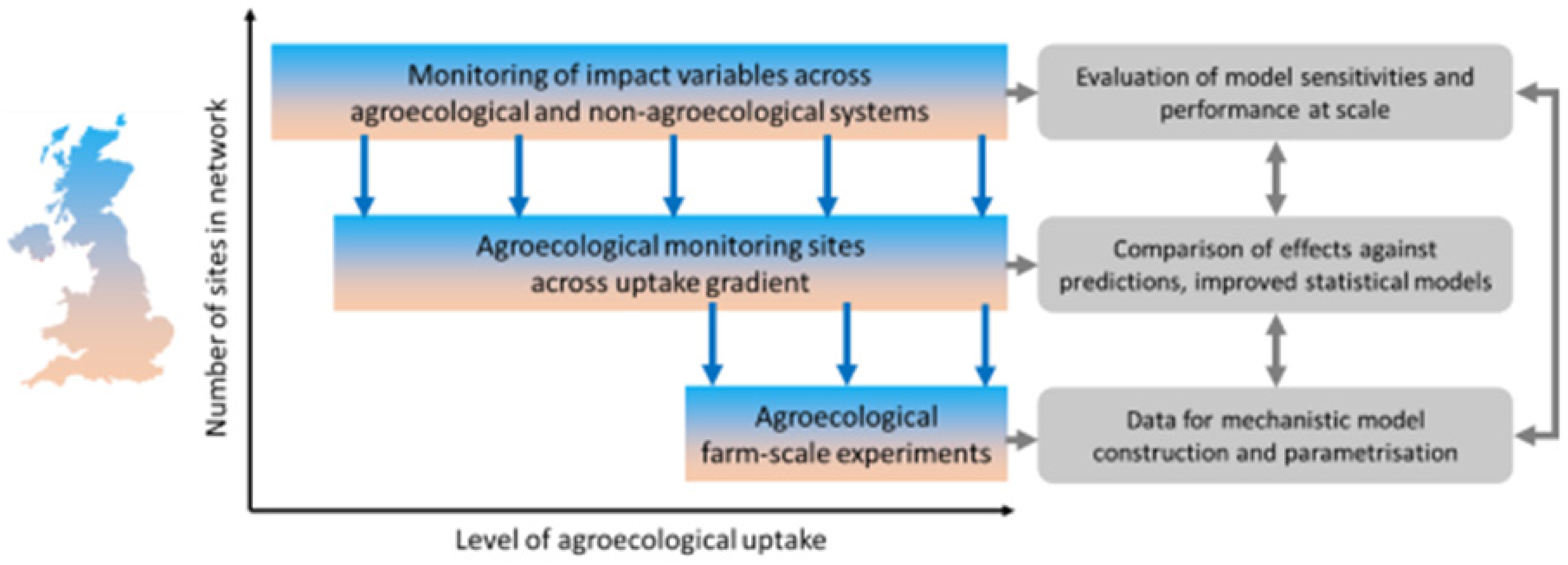

Figure 7. Schematic illustration of three levels of monitoring networks for agroecology (coloured boxes) and their potential use for agroecological modelling (grey boxes). The levels vary in their coverage of the agroecological uptake gradient and the number of sites in the network (as determined by the likely cost and effort in setting up and maintaining the network). The colour gradients indicate the requirement for each network to be representative of a range of UK contexts and conditions. Arrows between boxes indicates the importance of sites common across the three levels of monitoring to explore scalability and transferability.

reductions in yields were built into the simulations. There were also assumptions about dietary change among the population (slightly fewer calories, reduction in animal products, increase in plant protein). The model predicted positive effects on biodiversity and reductions in GHG emissions by 38%. Further work could be done using this framework to simulate regenerative agriculture scenarios using realistic input data on practices and productivity. This could help to build the evidence base about the impacts of regenerative farming systems on a wide number of societal and environmental indicators.

Exploring the impacts of transitioning towards regenerative agriculture at the landscape scale is crucial to understanding the effects of widespread uptake of such systems on greenhouse gas (GHG) emissions, the water cycle, and biodiversity. This type of analysis is essential if governments are to support the transition to regenerative farming. Some research work is already in place to study impacts on biodiversity (H3 Cambridge) and GHG emissions (Fix our Food, Leeds). Modelling approaches will be key to developing the evidence base for a transition to regenerative practices. Monitoring data is needed to parameterise and evaluate these models. Scenarios explored should be co-developed with farmers to ensure

realism. Future projects should build on the work of the Food Farming & Countryside Commission's report Farming for Change. This is a high-priority area for basic and applied research and will require multidisciplinary studies involving environmental modellers, social scientists and policymakers.

5.4 The impact of regenerative agriculture on product quality and end-market use

The use of regenerative agriculture practices may alter the final quality of the product in a way that affects its end-market use. In Section 5.5 we discussed product quality in terms of nutritional value for the consumer, but there may also be specific properties of crops grown using regenerative agriculture that affect its suitability for further processing. This was already discussed in Challenge 3.7 where we reviewed evidence that using genetically diverse plant materials can result in crop products that are of lower or less consistent quality.

Concerns about product quality may be linked to the lower N inputs used in regenerative agriculture. For cereals in particular, this can result in lower grain protein contents.

In the UK the minimum acceptable protein content for milling wheat is 13%. Wheat must also have a Hagberg Falling Number greater than or equal to 250s and a specific weight greater than or equal to 76 kg/hL. Wheat not meeting these specifications will normally be diverted to the feed wheat market. Mycotoxins in wheat can also be problematic if they are above the legal limits for livestock feed or human consumption. These mainly vary due to year and production region, but may also be affected by the previous crop, cultivation methods and variety, as well as cereal intensity in the rotation(6).

6. From:https://ahdb.org.uk/improving-risk-assessment-to-minimise-fusarium-mycotoxins-in-harvested-wheat-grain#:~:text=The%20majority%20of%20the%20variation,relevant%20government%20and%20industry%20bodies.

There are no projects that explicitly explore this topic, however, some past projects should provide useful data on actual quality parameters for crops grown under low-input/organic conditions. This data could be used in models to simulate potential effects of introduction of more regeneratively grown products to the market. HealthyMinorCereals(7) was an EU-FP7 project that investigated minor cereals like spelt, rye, oat, einkorn and emmer and the potential to expand their production and markets. Extensive data on crop quality was produced, and the impacts of the production methods on processing quality were studied. Prior to this, the QualityLowInputFood(8)project (EU-FP6) project studied the impacts of organic production systems on food quality (including processing parameters) and will have an extensive dataset of results that would provide a good starting point for modelling studies on regenerative systems.

Going forward, the Large-Scale Rotation Experiment at Rothamsted (which is run at two locations) will provide useful data on quality of crops produced under a range of regenerative management practices.

Regenerative agriculture practices may influence product quality, resulting in both benefits and drawbacks. For example, there may be lower pesticide residues and higher levels of some key micronutrients and secondary metabolites, but also negative effects such as lower protein levels in wheat. These changes could have ripple effects in the food system, such as more wheat being diverted to feed wheat markets or the need for developing new products for lower protein cereals. This is a high-priority area for applied research. Multidisciplinary work across the supply chain, including nutritionists and food scientists, is necessary to fully understand the implications of changes in product quality on markets and food security.

7. https://healthyminorcereals.eu/en/about-project/objectives

8. There is no longer a live website for this project, but outputs should be available through the CORDIS platform: https://cordis.europa.eu/project/id/506358/reporting

5.5 Impacts of regenerative agriculture on food quality, particularly nutrient density

“Nutrient density” has become a popular term used to describe the nutritional quality of foods, with a particular emphasis on the concentration of essential minerals, vitamins and beneficial compounds relative to the calorie content of the food. Foods with a high nutrient density provide more nutrients per calorie. However, consumers and health professionals still have no agreed definition for this term (Lockyer et al. 2020). Therefore, we expanded our search of peer-reviewed literature to include nutritional profile, nutritional content and quality, and nutrient density. When this search was combined with regenerative agriculture search terms, very few articles were identified.

Montgomery et al. (2022) explored the relationship between soil health and nutrient density, using a paired farm comparison approach where farms using regenerative practices (defined as no-till, cover crops, diverse rotations) were matched with a nearby conventionally managed farm (intensively tilled); indicators of soil health and nutrient density were measured for each of 9 pairs. They reported higher values for various nutritional compounds (total phenolics, vitamins K, E, B1, B2) in the regeneratively farmed samples. The authors speculated that soil organic matter and improved soil health were influencing phytochemical levels in the crops, but they also commented on the challenge of linking soil health and human health due to the complexity of soil ecology and the human microbiome.

A review was also conducted by Manzeke-Kangara et al. (2023) who used a very broad definition of regenerative agriculture to compile findings from studies that included organic inputs, reduced tillage, biostimulants, intercropping and even irrigation. They present a conceptual diagram illustrating the links between regenerative agriculture and human health and nutrition, proposing that improvements in soil health improve nutrient cycling by soil organisms which thereby affects crop nutritional quality. Their study is very detailed and provides a granular assessment of the impacts of specific practices on nutritional quality for a range of crops globally. They concluded that there is good evidence that regenerative agriculture practices increase crop micronutrient contents.

These effects are similar to findings from various studies which have compared organic and conventional production systems (e.g. see papers by Prof Carlo Leifert and his research group since the mid-2000s). These studies may provide some hypotheses to support the assertion that products of regenerative agriculture are different from conventionally produced foods. The lower levels of fertilizer inputs in organic systems appear to favour the production of plant secondary metabolites e.g. higher levels were reported for phenolics in potatoes, cabbages and lettuce, glucosinolates and carotenoids in cabbages, vitamin C in potatoes and cabbages, and vitamin B9 in potatoes and lettuce (Rempelos et al. 2023). It is possible that the higher levels of beneficial nutrients in organic compared to conventional foods previously reported in a range of meta-analyses and systematic reviews, are largely due to the non-use of synthetic N fertilisers in organic systems (Brandt et al. 2011; Barański et al. 2014; Rempelos et al. 2021). This finding was also reflected in the results of Shewry et al. (2018) who reported nutritional differences between inorganic N and low-input/FYM-based fertilization regimes in the Broadbalk experiment and a wider range of samples from organic experiments across Europe. Since regenerative systems also often use lower fertilizer inputs this outcome may also be expected, but further research is needed to confirm this.

Nutritional quality could be different when comparing regenerative and conventional systems because of varietal differences in the crops grown; many regenerative farmers are using genetically diverse crops including varietal blends (Challenge 3.7) and plant populations (Challenge 3.8). Soil health and levels of available nutrients, especially micronutrients, may also indirectly affect the quality of food produced in regenerative systems, as discussed by Montgomery and Biklé (2021).

The H3 project(9) (part of the UKRI's Transforming UK Food Systems programme) aims to assess the impacts of regenerative agriculture on food quality, thus providing valuable data from a UK context. Rothamsted's new Large Scale Rotation Experiment (10) includes

9. https://h3.ac.uk/

10. https://www.rothamsted.ac.uk/news/new-long-term-experiments-rothamsted-will-shed-light-potential-impacts-regenerative

nutritional quality as one of the key outcomes they will monitor; this will provide robust evidence on the relative effects of different regenerative agriculture practices that are experimental factors in the trial (compost amendment, cover crops and rotational diversity) on nutritional quality.

Linked to 5.4, food quality effects of regenerative farming practices are of interest in the marketplace. This is a challenging topic to study, in light of the lack of an agreed definition of regenerative (see Challenge 1.2). There have been numerous studies comparing the nutritional differences between organic and conventional foods; these should be reviewed and future studies designed that build on these findings. Studies within the UK context are important; and controlling for the multiple variables that can impact nutritional outcomes is necessary to answer this question. More basic research is needed to clearly define "nutrient density". This topic was ranked as high to normal priority by workshop stakeholders.

Project Summary

Appendix A summarises the results of the gap analysis based on the evidence reviewed in this project. To be considered a high priority for research, topics needed to have received more than 10 votes in the critical or high-importance categories in the initial stakeholder workshop. Topics were also considered priorities if there were few peer-reviewed papers found on the Web of Science (‹ 20 indicating minimal research activity globally on this topic) and a low number of UK projects and reports (fewer than five are shaded green to indicate a deficiency of activity in this area).

Impacts of the production system on product quality and end-market use (5.4), particularly with reference to wheat and effects on the feed vs. bread wheat market, ranks as a high-priority area for further applied research: few academic papers on this topic exist, and only three current and past projects were assessed as relevant to this topic. Multidisciplinary work across the supply chain, including nutritionists and food system modellers, is necessary to fully understand the implications of changes in product quality on markets and food security.

A key factor affecting uptake of regenerative agriculture is its impact on farm economics, and a better understanding of socio-economic factors constraining uptake of regenerative agriculture (6.2) is of critical importance to many stakeholders. This ties in with topic 6.1, The impact of regenerative agriculture systems on farm livelihoods, which workshop participants ranked as the top research priority. More information on the economic impacts of adopting regenerative agriculture practices is necessary, and this could be accomplished through farmer clusters e.g. Groundswell Agronomy or AHDB's Monitor Farm approaches.

"How to…" implement regenerative agriculture featured as a top priority, with the need for regionally adapted cover crops (2.6) of high importance to stakeholders and relatively few ongoing projects. However, some existing reports on cover crops should be referred to when developing future research activities. The Cover Crop Guide, recently developed by the Yorkshire Agricultural Society, has laid much of the groundwork for further work in this area.

Other “How to…” topics that were considered important included: 2.1 Growing root crops in regenerative systems, 2.2 Intercropping arable crops successfully, 2.5 Effective termination of cover crops; without herbicides, 2.7 Impacts of cover crops on weeds, pests and diseases, 2.8 Reducing herbicide use in regenerative systems, and 2.9 Integration of livestock into arable regenerative systems. The latter two topics emerged during discussions at the workshop and the Future of Farming conference. Some of these topics already have a large body of scientific information to support the development of applied research in the UK, e.g. root crops in regenerative (low disturbance tillage) systems are discussed in more than 100 academic papers. The same is true for intercropping, which has been researched extensively and would benefit from an applied/KE approach. Termination of cover crops is also discussed in many academic studies, but since its success is so dependent on the local environment, it will still be important to conduct research under UK conditions. Livestock are recognised as integral to regenerative agriculture but can present challenges to arable farmers; more applied research is needed to overcome the barriers to including animals in regenerative farming systems. All of these topics are best suited to applied research on farms, recognising that implementation of these diversified cropping approaches is highly context-dependent.

The identification of metrics to support the definition of regenerative agriculture (1.1) was identified as important by workshop attendees, and there are few academic papers or projects on this topic. There is a recognition that the main drive to define regenerative agriculture comes from researchers and a solid definition and metrics will be important if robust research on regenerative agriculture’s effects is to be conducted. A few UK projects have attempted to define regenerative agriculture and a consensus could be reached on a definition by collecting stakeholder input. It does seem key to decide if a practice-based definition (which is conducive to the development of standards and a certification system) or an outcomes-based definition (more inclusive of a range of practices and aligned with Defra targets like the Environmental Improvement Plan) is the way forward for the movement in the UK. An inclusive definition based on outcomes could facilitate more rapid uptake of practices and ultimately have a wider impact but may not allow niche access to markets that compensate farmers adequately for any loss in production.

Wider system impacts of regenerative agriculture need to be better documented to demonstrate the benefits of these practices. Impacts particularly on the water cycle (both flood risk and drought resilience; 5.1) need to be studied and understood. In addition, the net effects on greenhouse gas emissions are not known. Integrating legumes into rotations (5.2) can have a range of knock-on effects on emissions in the field and beyond the farm gate. A slightly broader statement on the wider impacts of regenerative agriculture on the environment also ranked highly (5.3 Practice and options to be assessed in terms of wider impacts), but it should be noted that there have been many papers published globally on environmental impacts of regenerative agriculture which should be reviewed before designing UK studies; various projects are ongoing that will also address these topics in the UK.

There is a perception that more crop breeding efforts should be targeted at traits important for regenerative farming. Variety evaluation and breeding for low N and pesticide inputs (3.3) was a high priority among workshop participants and has also been identified as important to levy payers in the recent AHDB Recommended List review process. Variety evaluation and breeding for weed competitiveness (3.4) and performance in reduced tillage systems (3.5) emerged as important topics at the workshop. These topics have been covered in peer-reviewed studies, but there have been few projects in the UK.

In addition, this study has highlighted the predominance of cereals, particularly wheat, in most breeding efforts. There is tremendous scope to extend breeding programmes to the less dominant arable crops (e.g. pulses, minor cereals like oats, spelt) and cover crops to help facilitate the transition to regenerative agriculture in the UK.

Among the topics within the Soil Health challenge, the need to understand the impacts of changes in soil biology on weeds (4.2) was particularly highly scored. There is some basic knowledge on the underlying mechanisms (a moderate number of peer-reviewed papers relating to the topic) but further basic soil science and applied research is needed. We did not identify any relevant projects on this topic and only one report from the grey literature. The impacts of strategic (occasional) tillage vs glyphosate on soil health (4.5) garnered significant interest among stakeholders at the workshop and was also identified in discussions at the Future of Agriculture conference.

There have not been many papers published that explicitly address this topic, however, there are several past and current experiments in the UK that include rotations, tillage and herbicide use as factors that could be used to begin to address this research topic.

Authors' Recommendations

This study has clearly mapped out the status of the research needed to support the transition to regenerative agriculture in the UK. It has showcased the extensive knowledge accumulated from past projects and the expertise of scientists, industry experts, and farmers in the sector. The detailed report and database are key resources that can be used to build an action plan to tackle the obvious knowledge gaps. The database could be made publicly accessible and maintained as a living resource for anyone looking for information on past and current projects and research relating to regenerative agriculture.

The next steps should be to develop a strategy to tackle each of the six challenge areas by forming working groups with the key individuals and organisations identified in the database. These groups could develop action plans that include accessing the Farming Futures funding opportunities that are currently live and partnering with research organisations and farmer groups (clusters) to develop local solutions to production challenges. In addition, the report can be used as evidence to lobby Defra and UKRI to support research programmes in these high-priority areas. Many of the priority areas reflect actions within the Sustainable Farming Incentive. Research on these topics will help build the evidence base for the SFI and other future farming and land management policies.

Key to the success of new programmes to support regenerative agriculture will be efficient and targeted use of resources. This means not reinventing the wheel and building on past experiences and knowledge. This study has helped to develop the resources needed to do this effectively.

The full report on this project (including full bibliography and appendices) and the database listing projects and reports can be found at www.organicresearchcentre.com

Appendix A

Summary table of top priority research topics based on outcomes of the stakeholder workshop, Future of Agriculture Conference and scoping of past and ongoing research. Projects included are only UK-based activities. Code numbering relates to the Challenges identified in this series of publications. "Grey literature" refers to reports from UK government and industry bodies, e.g. AHDB, NIAB. Colour shading is provided to indicate highest priority/largest gap (green), moderate priority/gap (amber) and lower priority/smaller gap (putty). Topics with the most "green" shading can be interpreted as top priorities.

		Workshop Outcomes		Scoping Study Outcomes			
Code	**Description**	**Critical+High Votes >10**	**Research Type**	**Peer-reviewed papers**	**Ongoing projects (total 27)**	**Past projects (total 28)**	**Grey literature (total 76)**
High priority with few academic papers or UK projects							
5.4	Impact of regenerative agriculture on product quality and end-market use	13	Applied	<20	1	2	0
6.2	Socio-economic factors constraining uptake of regenerative agriculture	11	Policy	<20		1	6
2.6	Regional adaptation of cover crops, particularly for cool, wet, temperate climates	11	Applied	<20	2	2	13
1.1	Identification of metrics to support definition	10	Policy	<20		1	6
High priority, some academic papers, some UK projects							
6.1	Impact (and the factors affecting it) of regenerative agriculture systems on farm livelihoods	19	Applied/KE	20-100	11	2	7
5.1	Impacts of regenerative agriculture systems on the water cycle (flood risk, drought)	13	Applied	20-100	3	2	3
3.3	Variety evaluation and breeding for low N and pesticide inputs	12	Applied	20-100	3	3	7
2.7	Impacts of cover crops on weeds, pest and diseases	11	Applied	20-100	3	3	4
4.2	Impact of changes in soil biology on weeds, particularly blackgrass	11	Basic/Applied	20-100			1
High priority, many academic papers, some UK projects							
2.2	Intercropping arable crops successfully	12	Applied/KE	>100	2	4	7
2.5	Effective termination of cover crops; without herbicide; impacts on the following crop	13	Applied	>100	3	2	8
5.2	Impacts of integration of legumes throughout the cropping system on N cycling including GHG emissions	12	Applied	>100	7	3	
5.3	Practice and options for regenerative agriculture to be assessed in terms of wider impacts	12	Applied	>100	8	3	13
2.1	Growing root crops in regenerative systems	11	Applied	>100	3		2
Topics not ranked during the stakeholder workshop							
2.8*	Reducing herbicide use in regenerative systems	NA	NA	20-100	1		9
2.9*	Integration of livestock into arable regenerative systems	NA	NA	<20	2	1	2
3.4*	Variety evaluation and breeding for weed competitiveness	NA	NA	>100	1		3
3.5*	Variety evaluation and breeding for performance in reduced tillage systems	NA	NA	>100	1	1	
4.5*	Impacts of strategic (occasional) tillage vs glyphosate on soil health	NA	NA	20-100	7	4	7

Bibliography

Albanito F, Jordon M, Abdalla M, et al (2022) Agroecology-a Rapid Evidence Review Report prepared for the Committee on Climate Change Final. Aberdeen

Barański M, Średnicka-Tober D, Volakakis N, et al (2014) Higher antioxidant and lower cadmium concentrations and lower incidence of pesticide residues in organically grown crops: A systematic literature review and meta-analyses. British Journal of Nutrition 112:794–811

Berdeni D, Turner A, Grayson RP, et al (2021) Soil quality regeneration by grass-clover leys in arable rotations compared to permanent grassland: Effects on wheat yield and resilience to drought and flooding. Soil Tillage Res 212:105037. https://doi.org/10.1016/j.still.2021.105037

Brandt K, Leifert C, Sanderson R, Seal CJ (2011) Agroecosystem management and nutritional quality of plant foods: The case of organic fruits and vegetables. CRC Crit Rev Plant Sci 30:177–197. https://doi.org/10.1080/07352689.2011.554417

Burgess PJ, Redhead J, Girkin N, et al (2023) Evaluating agroecological farming practices. DEFRA Project SCF0321 Report

Collins SL, Verhoef A, Mansour M, et al (2023) Modelling the effectiveness of land-based natural flood management in a large, permeable catchment. J Flood Risk Manag 16:e12896. https://doi.org/10.1111/jfr3.12896

Cooledge EC, Chadwick DR, Smith LMJ, et al (2022) Agronomic and environmental benefits of reintroducing herb- and legume-rich multispecies leys into arable rotations: a review. Front Agric Sci Eng 9:245–271. https://doi.org/10.15302/J-FASE-2021439

Eory V, Topp K, Rees B, et al (2020) Marginal abatement cost curve for Scottish agriculture. Edinburgh

Erekalo KT, Pedersen SM, Christensen T, et al (2024) Review on the contribution of farming practices and technologies towards climate-smart agricultural outcomes in a European context. Smart Agricultural Technology 7:100413. https://doi.org/10.1016/j.atech.2024.100413

Hansen S, Frøseth RB, Stenberg M, et al (2019) Reviews and syntheses: Review of causes and sources of N2O emissions and NO3 leaching from organic arable crop rotations. Biogeosciences 16:2795–2819

Liu L, Dobson B, Mijic A (2023) Optimisation of urban-rural nature-based solutions for integrated catchment water management. J Environ Manage 329:117045. https://doi.org/10.1016/j.jenvman.2022.117045

Lockyer S, Cade J, Darmon N, et al (2020) Proceedings of a roundtable event 'Is communicating the concept of nutrient density important?' Nutr Bull 45:74–97. https://doi.org/10.1111/nbu.12421

Manzeke-Kangara MG, Joy EJM, Lark RM, et al (2023) Do agronomic approaches aligned to regenerative agriculture improve the micronutrient concentrations of edible portions of crops? A scoping review of evidence. Front Nutr 10:1078667

Montgomery DR, Biklé A (2021) Soil Health and Nutrient Density: Beyond Organic vs. Conventional Farming. Front Sustain Food Syst 5:699147

Montgomery DR, Biklé A, Archuleta R, et al (2022) Soil health and nutrient density: preliminary comparison of regenerative and conventional farming. PeerJ 10:e12848. https://doi.org/10.7717/peerj.12848

Poux X, Schiavo M, Aubert P-M (2021) Modelling an agroecological UK in 2050-findings from TYFA REGIO

Ramos Huarachi DA, Piekarski CM, Puglieri FN, de Francisco AC (2020) Past and future of Social Life Cycle Assessment: Historical evolution and research trends. J Clean Prod 264:121506. https://doi.org/10.1016/j.jclepro.2020.121506

Rehberger E, West PC, Spillane C, McKeown PC (2023) What climate and environmental benefits of regenerative agriculture practices? an evidence review. Environ Res Commun 5:052001. https://doi.org/10.1088/2515-7620/acd6dc

Rempelos L, Barański M, Sufar EK, et al (2023) Effect of Climatic Conditions, and Agronomic Practices Used in Organic and Conventional Crop Production on Yield and Nutritional Composition Parameters in Potato, Cabbage, Lettuce and Onion; Results from the Long-Term NFSC-Trials. Agronomy 13:1225. https://doi.org/10.3390/agronomy13051225

Rempelos L, Baranski M, Wang J, et al (2021) Integrated soil and crop management in organic agriculture: A logical framework to ensure food quality and human health? Agronomy 11:2494. https://doi.org/10.3390/agronomy11122494

Shewry P, Rakszegi M, Lovegrove A, et al (2018) Effects of Organic and Conventional Crop Nutrition on Profiles of Polar Metabolites in Grain of Wheat. J Agric Food Chem 66:5346–5351. https://doi.org/10.1021/acs.jafc.8b01593

Singh P, Nazir G, Dheri GS (2023) Influence of different management practices on carbon sequestration of agricultural soils–a review. Arch Agron Soil Sci 69:2471–2492

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241:155–176. https://doi.org/10.1023/A:1016125726789

Tamburini G, Bommarco R, Cherico Wanger T, et al (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci Adv 6:eaba1715

Weiner M, Moakes S, Raya-Sereno MD, Cooper J (2024) Legume-based crop rotations as a strategy to mitigate fluctuations in fertilizer prices? A case study on bread wheat genotypes in northern Spain using life cycle and economic assessment. European Journal of Agronomy 159:127267. https://doi.org/10.1016/j.eja.2024.127267

Organic Research Centre, Trent Lodge, Stroud Road, Cirencester, Gloucestershire. GL7 6JN

01488 658 298 | hello@organicresearchcentre.com | organicresearchcentre.com

Photography the courtesy of Phil Sumption, Dr. Julia Cooper and Paul Muto.