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

Challenge 2 (of 6): Advice and Guidance or "How to..."

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Thank You

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Backround/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 2: Advice and Guidence or "How to...". The findings of the other challenges can be found in the associated series of publications available at www.organicresearchcentre.com.

2.1 Growing root crops in regen systems

A large number of the challenges identified in the project were linked to a need for advice and guidance or "How to…" implement a specific regen ag practice. This section reviews a number of these challenges and makes recommendations about how to address them. In general, these challenges may be best addressed through on-farm experiments with networks of trials that embed the knowledge exchange within the agricultural community. Farming systems approaches will be essential, which take into account the context of the experiments and use innovative data analysis methods to elucidate the interactions between environmental and management factors.

The production of root crops in regenerative systems was identified by stakeholders as particularly challenging. This challenge is associated with the high levels of soil disturbance normally associated with root crops and the requirement for minimal soil disturbance in regenerative agriculture. Burgess et al. (2023) in their report to Defra highlighted the yield gaps commonly reported when root crops are grown in no-till systems.

A search string that included the following terms that could be used to describe reduced tillage intensity was used with the TS category(3) : "no-till" OR "no till" OR "conservation till" OR " zero till" OR "direct seeding" OR "direct drill" OR "strip-till" OR "strip-till" OR "minimum till" OR "min till" OR "reduced till" OR "reduced intensity till". This was combined with a term for root crops (TS=("carrots" OR "potatoes" OR "turnips" OR "swedes" OR "radishes" OR "beets" OR "rutabagas"). The outcome of this search was very few papers published with no studies in the UK(4) .

Bietila et al. (2017) described a cover crop-based reduced tillage (CCBRT) system for vegetables in the US mid-west using rye or wheat terminated at anthesis as a mulch for no-till planting of the potato tubers. In this experiment the tubers were planted by hand; there was no yield penalty for the mulched treatments, but clearly equipment adaptation would be needed to make this system practical on a field scale.

3. includes article topic, title, abstract and author keywords

4. "in the UK" implies authors with UK country addresses; it does not necessarily mean studies were done in the UK

The Oberacker long-term field experiment in Germany has been run for over 20 years and compares mouldboard ploughing with no-till in a six-year rotation (peas - winter wheat - field beans - winter barley - sugar beet - silage maize (Martínez et al. 2016). The sugar beet is established using a no-till drill, but there is some soil disturbance during harvest. Yields of sugar beet have been lower in this experiment; this was attributed to higher resistances to penetration in the no-till topsoil. A German study included sugar beet in a tillage trial; they reported yields about 6 t ha-1 lower for no-till production compared with ploughing and stubble tillage(5) (Gruber et al. 2012).

In the UK McCain's has launched its Smart & Sustainable Farming Programme in collaboration with NIAB's Farming Systems Research team, which promotes six key principles of regenerative agriculture and supports its farmers to progress through four levels of expertise: Onboarding, Beginner, Master and Expert. The framework also includes a commitment to develop research partnerships. McCain's also recently joined a consortium with PepsiCo and various Universities and companies to deliver the PotatoLITE(6) (Low Intensity Tillage Enhancement) project funded by Defra and UKRI's Farming Innovation Programme. The project aims to "develop novel machinery and cultivation practices for UK-based potato farms to optimise tillage intensity, improve soil health and lower greenhouse gas (GHG) emissions".

This project should lay the groundwork for a programme of research into how to include root crops in systems with reduced tillage. The involvement of soil scientists and equipment manufacturers, as well as big potato processors like McCain's, should help to ensure an effective research programme is developed.

Root crops have not been a focus of regenerative agriculture research up to this time, but as the UK transitions to more integrated and diverse crop rotations and more locally produced food, root crops will need to be included in regenerative systems. Production systems for root crops are recognized as being very damaging to soil health, so it makes sense to develop regenerative practices for rotations with root crops. The initiatives of PepsiCo and McCains highlighted above should be laying the groundwork for innovative ways to include root crops in regen farming systems.

5. Stubble tillage is a term used in Europe to refer to a light harrowing prior to ploughing to control weed
6. https://potato-lite.farm/

This study identified root crops (e.g. potatoes, carrots) in regenerative systems as a high priority for applied research. We recommend connecting with the PotatoLITE team to identify gaps and find ways to take the project further. Engaging with equipment manufacturers and engineers will also be crucial. Additionally, collaborating with projects focused on soil organic matter management, such as the ORC Feed the Soil project, will help develop strategies for using compost and other amendments to improve soil health throughout all rotation phases where root crops are included.

2.2 Intercropping arable crops successfully

Intercropping is an umbrella term that can refer to strip, row, relay, and mixed intercropping as well as companion planting and living mulches (see below). It has been researched extensively over many years; with a particular increase in activities since the turn of the last century (Landschoot et al. 2023; Zustovi et al. 2024). For the purposes of this study, we have focussed the gap analysis on intercropping of annual crops, defined by the "arable" search term TS=(arable OR cereal OR rapeseed OR canola OR wheat OR barley OR oats OR beans OR maize). This aligns with the definition provided in a recent review by Dzvene et al. (2023) where intercropping is described as: the general practice in which component crops provide harvestable grain yield benefits. The total number of publications about intercropping with arable crops found on the Web of Science was 6,475, with over 200 of those publications having authors based in the UK. This demonstrates that there is already a considerable body of knowledge on this topic. To rapidly assess the gaps in cereal-legume intercropping, the papers were filtered to include only reviews and sorted by date; the top 12 papers were downloaded and reviewed in detail to extract key research questions identified by the authors.

Mouratiadou et al. (2024) included intercropping as one of the agroecological practices they evaluated in a detailed review of socio-economic performance of agroecology(7). They reported positive effects of intercropping on income and revenue and, to a lesser extent, on productivity and efficiency (bearing in mind this is a global review; results in the UK may not reflect this pattern). Less positive results were reported for labour requirements, but again, this is for a global study that includes smallholder systems where labour is manual and complexity in crop arrangement can increase time for manual tasks. This study uses a framework that could be applied to regenerative practices in the UK to gather some useful economic data (see Challenge 6.1).

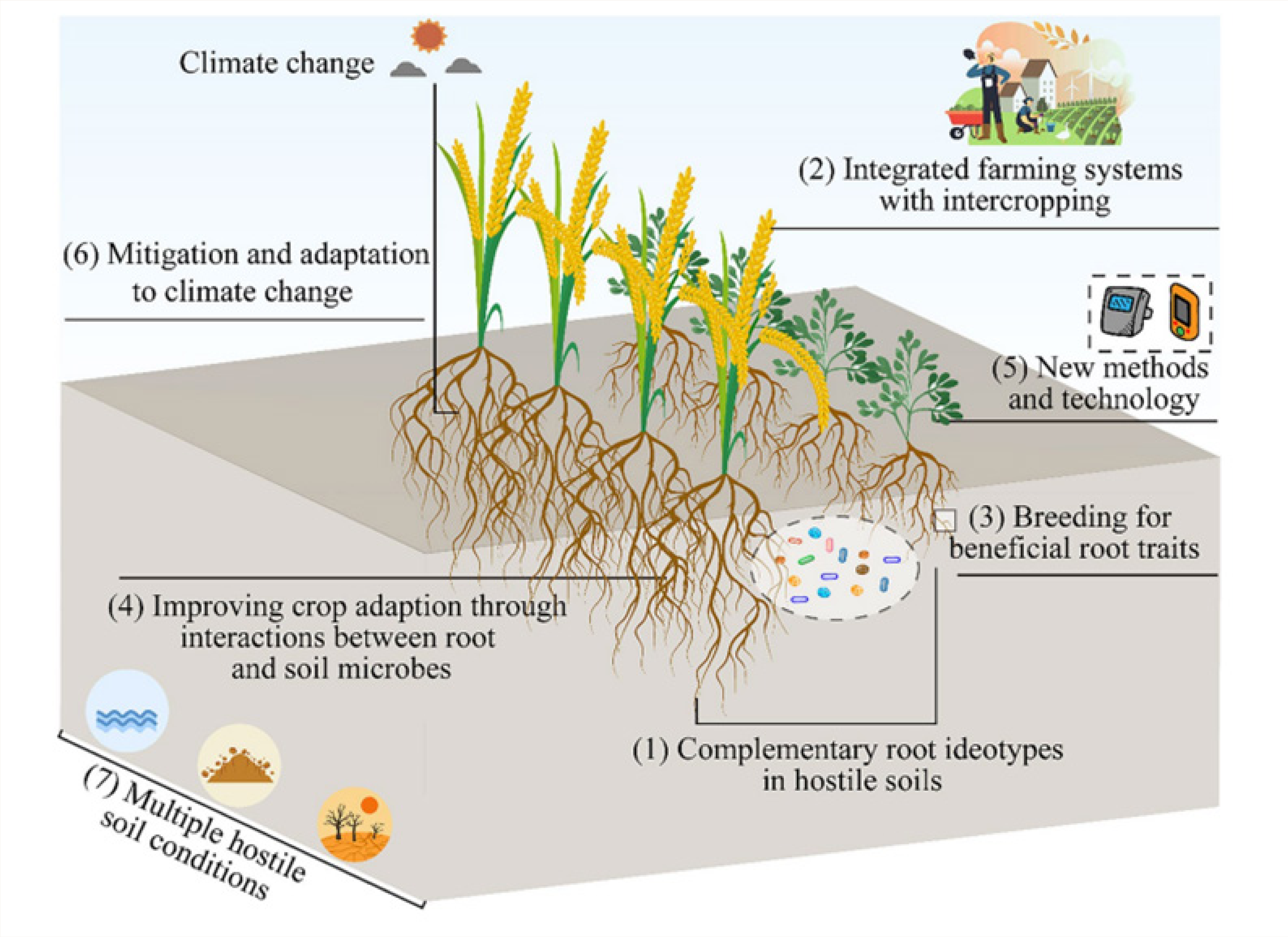
7. It is interesting to note that the authors excluded intercropping systems that used genetically modified crops or high rates of pesticides as these were deemed to be outside the scope of agroecological systems.

Zustovi et al. (2024) highlight the current level of interest in intercropping but also point out that machinery and equipment suited to intercropping systems is lacking and that this may be constraining uptake. Their review focussed on the more than 20 indices currently used in the academic literature to characterise impacts of intercropping on performance and recommended creating a standard protocol for intercropping trials and their evaluation as crucial elements to optimise intercropping research. This should certainly be agreed upon in the UK to ensure a useful interpretation of results.

Zhang et al. (2024) offer several perspectives on future research topics in intercropping with a focus on roots (Figure 1). While their review was focused on "hostile" soils (meaning those prone to drought and salinity), their suggested focus areas are still relevant to UK systems. They emphasise the importance of complementary root traits in intercropping systems (1), referring to the topsoil foraging root ideotypes which are contrasted with the "steep, cheap and deep" ideotypes needed to access deeper resources. Characterisation of root structures remains a challenge, which ties in with the need for new methods and technologies (5) to study roots in intercropping systems. They point out the need to adapt intercropping within "integrated" (which could be read as "regenerative") farming systems. This highlights the need to develop and test intercropping methods within systems that include other regenerative practices(2) e.g. no-till/minimal soil disturbance, reduced pesticide and nutrient inputs, living mulches etc. Breeding for beneficial root traits (3), including deep rooting, the proliferation of lateral roots and root hairs, is important in monocultures grown under reduced inputs, but Zhang et al. (2024) acknowledge that intercropping systems may exacerbate competition for limiting nutrients and suggest that breeding for these root traits could be particularly important in intercrops. Just as understanding root-microbiome interactions (4) is important in monocrops within regenerative systems, it is also important in intercrops with the microbiome regulating interspecific competition in intercrops, suppressing pathogens and increasing beneficial microbes. The changes in soil microbial community structure and enzyme activities depending on the intercrops present were also highlighted by Gao and Zhang (2023) who reported higher levels of soil microbial diversity in intercrops; however, the impact of these changes on soil functions and crop productivity has still not been demonstrated. There remains a gap in knowledge around the interpretation of soil microbiome information and translation into actionable recommendations.

The potential of intercrops to future-proof cropping systems against climate change (6), is alluded to e.g. against waterlogging which may happen more frequently in the future. This seems particularly relevant this year when unprecedented rainfall has led to crop failures in the UK. Intercrops may provide resilience against these climate extremes, but research is needed to understand the best combinations of species and varieties to achieve this resilience; long-term trials were highlighted as important for climate resilience research.

Figure 1: Image from Zhang et al (2024) illustrating seven areas for future research activities relating to roots and intercropping systems.



Landschoot et al. (2023) conducted an extensive literature review that included common intercrops such as maize and soybeans as well as underutilised crops like lupins and buckwheat. The majority of papers identified focussed on soybeans, maize and wheat; an opportunity for more studies on underutilised crops (e.g. oats, triticale) was identified.

Schöb et al. (2023) reported on a series of experiments across Europe (The Crop Diversity Experiment) and speculated that genotypes could be selected for improved performance in mixtures. They suggested evolutionary breeding approaches using mixtures of genotypes as an approach to optimize cultivars for growth in crop species mixtures. Księżak et al. (2023) also concluded that more research into the impacts of higher intraspecific diversity (genotype mixtures) within intercrops was needed.

Rakotomalala et al. (2023) used a meta-analysis approach to demonstrate the positive effects of intercropping on beneficial arthropods. They recommended moving beyond field-level studies to the landscape scale to better understand the interactions between surrounding landscapes and intercropped areas; they also recommended long-term studies to evaluate the stability of the effects over time.

Several past projects have produced useful, practical information on intercropping in the UK. This includes the Nuffield Scholarship report written by Andrew Howard(8) which identified a need for breeding varieties adapted to intercropping(9) systems and collaboration between farmers and equipment designers to develop machinery tailored to intercropping systems. Andrew was part of an Innovative Farmers project on intercropping trialling oats and linseed, oilseed rape and peas, and wheat and beans; results for the oats and linseed were promising with higher yields of linseed in the intercrop.

There have been a few intercropping projects in the UK (Table 1) with two still ongoing: Leguminose and New Farming Systems. The DiverIMPACTS project developed a list of resources to assist farmers with decision-making about the diversification of cropping systems (TOOLBOX FOR CROP DIVERSIFICATION (shinyapps.io)). A detailed review of these projects' outcomes should be conducted before planning a research or knowledge exchange programme on intercrops.

8. https://agricology.co.uk/resource/potential-companion-cropping-and-intercropping-uk-arable-farms/
9. https://www.innovativefarmers.org/field-labs/intercropping-in-arable-farming/

Intercropping has already been widely researched globally and in the UK. Future activities in the UK should build on this knowledge base. Topics identified still in need of further research include:

- Standardize protocols for intercropping trials and their evaluation
- Study rooting traits in intercropped species
- Crop breeding for varieties with rooting traits (and other traits) that are suited to intercropping systems
- Understand root-microbiome interactions in intercropping systems
- Include studies on intercropping of underutilised crops (e.g. oats, triticale)
- Collaboration with equipment designers to develop machinery tailored to intercropping systems

Table 1 Recent and ongoing projects on intercropping in the UK

Project Title	Lead Organisation	Website	Start Year	End Year
Diversify - Designing Innovative plant teams for ecosystem resilience and agricultural sustainability	James Hutton Institute	https://plant-teams.org/	2017	2021
Leguminose	Reading University	https://www.leguminose.eu/the-project/	2022	2026
DiverIMPACTS - Diversification through Rotation, Intercropping, Multiple cropping, Promoted with Actors and value-Chains Towards Sustainability	Organic Research Centre	https://www.organicresearchcentre.com/our-research/research-project-library/diversification-through-rotation-intercropping-multiple-cropping-promoted-with-actors-and-value-chains-towards-sustainability/	2017	2022
Intercropping in arable farming	Soil Association	https://www.innovativefarmers.org/field-labs/intercropping-in-arable-farming/	2018	2019

The need for practical guidance on all types of intercropping, highlighted by Andy Cato at the Future of Farming conference, has been echoed by many farmers. This is a high-priority area for applied research and knowledge exchange. Adapting knowledge exchange information and tools from past intercropping projects for use in the UK would be beneficial. Forming a stakeholder group that includes project leads from Leguminose would help prioritise actions on this topic.

2.3 Companion planting successfully

Companion planting is a specific type of intercropping that has been developed to mitigate insect pests and enhance pollination: as such, it is focused very much on plant-insect interactions and how these can be managed in main crops through the presence of intercrops. This definition has been expanded upon by Woolford and Jarvis (2017), to include intercrops grown to provide nutrients, or act as a nurse crop that can help to increase crop productivity (as opposed to as an additional cash crop). For this review, most resources identified are related to the pest management function of companion cropping.

Trap cropping is one type of companion cropping in which the diversification of vegetation in a field or garden is used to attract insect pests away from main crops during a critical time period by providing the pests with an alternative food source (Sarkar et al. 2018). Companion plants may also moderate insect pests by releasing volatile organic compounds (VOCs) which repel pests(10) and/or attract the natural enemies of pests (Mofikoya et al. 2019). A third type of companion planting involves growing pollinator-attracting plants in close proximity to crops that are reliant on pollination for production of good yields (Montoya et al. 2020).

Only six papers were identified in the Web of Science searches that explicitly used the term "companion planting" in the TS fields. Brassicas (mainly cabbage and broccoli) are the most commonly studied crops in companion planting systems (Hooks and Johnson 2003). Hooks and Johnson (2003) conducted a comprehensive review of these systems covering mechanisms affecting pest behaviour and management interventions to moderate pest pressure using companion plants. Cabbage stem flea beetle (CSFB) is a particularly troublesome pest in oilseed rape crops in the UK, and seed companies have promoted companion plants (e.g. Berseem clover) in oilseed rape as a deterrent to this pest. Effects may be linked to the height of the clover e.g. plants that are taller than the crop can reduce egg laying by pests (Hooker and Johnson 2003). Companion crops such as white clover may reduce the laying of eggs by Delia brassicae Bohe (Hooks and Johnson 2003). Companion plants need to have a significant degree of growth to be effective; e.g. 50% of the vertical profile of the crop plants (Hooks and Johnson 2003).

10. In academic literature insect pests which consume crops are sometimes referred to as herbivores

Seimandi-Corda et al. (2024) conducted trials in the UK and Germany to test the impacts of intercropped companion plants (white mustard, Berseem clover, wheat, barley or oats), a turnip rape trap crop border, or simply chopped straw, on CSFB infestation in oilseed rape. Cereals like wheat or oats, which were included to simulate volunteer cereals in a rape crop, were particularly effective at reducing the pest damage. Even chopped straw was effective; in spite of the promotion by the seed industry, the clovers tested in the experiments were not as effective as cereals at reducing pest infestation. In general, the importance of ensuring good cover by the companion crop was highlighted as key to reducing CFSB damage.

Panwar et al. (2021) provide a detailed review of trap cropping explaining the various modes of action and designs of the systems. These include:

- Conventional trap cropping: a trap crop planted next to a higher value crop is naturally more attractive to a pest as either a food source or oviposition site than is the main crop
- Genetically engineered trap cropping: which uses GE techniques to breed trap crops that are particularly effective at drawing pests away from the main crop (this is also alluded to by Pickett et al 2019)
- Dead-end trap cropping: uses trap crops that are very attractive to pests but do not allow the pest to survive or reproduce
- Multiple trap cropping: planting several species together
- Perimeter trap cropping: planting the trap crop around the perimeter of the main crop
- Sequential trap cropping: planting the trap crop before or after the main crop, and
- Push-pull trap cropping: uses a combination of strategies to repel (push) the pests away from the cash crop while at the same time pulling pests towards other areas (e.g. trap crops) where they are concentrated and can then be eliminated

In the UK there have been a few projects that have investigated companion planting methods in the field. A 2009 project commissioned by Defra (Companion Planting for Pest Control in Field Crops - HL0174LFV) explored the potential to use companion planting to reduce pest pressure from cabbage root flies(11) .

11. Much of the evidence to support this theory was provided from insect behaviour studies done at Warwick HRI during collaborations between Stan Finch, Rosemay Collier and three visiting workers/students (Kostal, Kienegger, Billiald [15,16,6]).

The researchers theorised that the colour, size and shape of companion plants, rather than the volatile chemicals they release, determine their effectiveness in reducing insect colonisation.Andrew Howard’s Nuffield report highlights some future research needs, particularly with regard to the need for improvements in crop breeding for intercropping systems and the development of appropriate equipment.

An exciting new long-term experiment has been established by Rothamsted Research that has three rotations (3-year, 5-year, 7-year) representing a gradient in crop diversity and two levels of tillage (conventional inversion tillage or reduced tillage) (Li et al. 2023). Half of all the plots have a “smart crop protection” or SCP treatment applied that includes companion planting for pest control. This complex Large Scale Rotation Experiment (LSRE) is established at Brooms Barn in Suffolk and Harpenden in Hertfordshire. Preliminary results for the first 4 years of the experiment are reported by Li et al. (2023) with no significant effects yet due to the SCP treatment.

This biological approach to pest management has previously received relatively little attention. While not identified as a top priority, there is a need for more fundamental research (understanding mechanisms) and applied research and knowledge exchange to improve guidance on this approach. We recommend forming an expert group to design a comprehensive program that includes fundamental and applied research and knowledge exchange, such as farmer case studies. Involving crop breeders in selection of specific varieties better suited as companion crops will also be crucial.

2.4 Using living mulches successfully

A living mulch is an "intercropped cover crop that provides non-harvest benefits" in arable cropping systems (Dzvene et al. 2023). Studies on living mulches in the UK were conducted at least as long ago as the early 1990s at the Institute for Grassland and Environmental Research (IGER) in North Wyke, Devon. Results from these studies published by Jones, Schmidt and Clements (Jones 1992; Jones and Clements 1993; Clements and Donaldson 1997; Schmidt et al. 2001) will provide useful baseline evidence on the positive effects (on N use efficiency, biodiversity) and challenges of growing wheat in a white clover understorey. More recent interest in these systems has developed in the conventional regen farming community due to a recognised need to reduce reliance on herbicides (particularly glyphosate) for termination of cover crops and control of weeds in no-till systems. Organic farmers are reliant on deep inversion tillage to destroy cover crops and control weeds: their interest in living mulches has arisen out of a desire to reduce tillage in their systems and living mulches offer an opportunity to do this. Wildfarmed®, which produces grain under their regenerative brand, supports the use of living mulches in their systems: they are also driving interest in this approach to cereal production.

When reviewing the evidence on living mulches it is apparent that living mulches cover a spectrum of approaches including short-term annual covers that may be overseeded into an established cash crop e.g. as in the study reported by Kunz et al. (2016) where cover crops were sown into a sugar beet crop after sowing the main crop, through to perennial covers, e.g. maize drilled into established white clover as described in Dzvene et al (2023).

There is a general need for research into living mulch species morphologies and physiologies so that systems can be designed that achieve the perfect balance between growth and development of the living mulch, sufficient to suppress weed competition and provide rapid soil cover while not directly competing with the main crop.

The No till and living mulches project was run by the Soil Association (2020-22) in collaboration with the Organic Research Centre and continued for a further year by the ORC (2023). Full reports on this project are available on the ORC website (here).

This "sweet spot" is sometimes referred to as "interspecies complementarity." A recent review by Cougnon et al. (2022) argued that a dedicated breeding programme is needed for living mulches and proposed an ideotype that has a pronounced winter dormancy, starting its growth late in spring such that the cereal can take a lead in development in winter and spring; short with a non-erect growth to limit competition for light with the crop; and, abundant seed production resulting in an acceptable seed price.

In the UK, farmers have tended to default to white clover varieties that are small leaved e.g. AberAce, AberPearl, Rivendell, to minimise competition with the main crop. Clovers have also been chosen due to the perception that the clover will transfer fixed N to the main crop thus reducing crop fertiliser needs. There may be other leguminous species more suited as living mulches, for example shorter varieties of Birdsfoot Trefoil or Black Medick.

Andrew Howard included living mulches in his Nuffield study and provides some useful advice. His section on undersowing advises planting legumes in wheat at GS22 to avoid problems with competition early in the season; this could be a way of establishing a living mulch for direct drilling of a cash crop in the autumn or following spring. He recommends medick and red clover for competition against weeds; sheep's fescue, white clover, bird's foot trefoil and lucerne are also recommended in his report. Other projects (e.g OSCAR, see box) have suggested that hairy vetch and subterranean clover have potential as alternative living mulch species (Bürki et al. 2001; Costanzo and Bàrberi 2016; Baresel et al. 2018). Subterranean clover may not survive the winters in the UK but could be suitable as an annual cover to be planted at the same time as a spring-sown arable crop.

A key research gap identified by the OSCAR project was the need for breeding and selection for new subsidiary crops with a focus on the selection for disease resistance and for combining ability of main crops with living mulches. In addition, research into automation, sensor technology and robotization should be supported. The project also produced a "wiki" described as an interactive user-fed knowledge source of regionally relevant information about complementary means to diversify agricultural systems" (12), a database on subsidiary crops (13) and a decision support tool to help filter the database to find the best crop for the user's situation (14); all of these valuable resources could be updated and adapted for use in the UK.

The OSCAR (Optimising Subsidiary Crop Applications in Rotations) project was a European project that used the term "subsidiary crop" to refer to cover crops that are grown for the ecological services they provide rather than as a cash crop. The project covered many practical aspects of the use of subsidiary crops including identifying new species and genotypes for use as living mulches (and cover crops) and development of new farm technology and machinery to facilitate their cultivation. It is important to build on this work, rather than reinventing the wheel, in future projects relating to subsidiary crops

Using perennial covers (living mulches) in arable systems is a key strategy to reduce reliance on herbicides, particularly glyphosate. This topic was scored in the workshop as high/normal priority for applied research. Scientists and farmers should co-design trials to test establishment methods, including equipment and timing. Additionally, a targeted program is needed to select, evaluate and/or breed varieties with suitable traits for these systems, and arable crop breeding programs could integrate assessment of inter-species competition as a valuable trait. Lessons from a living mulch network could be shared through existing decision support tools (e.g., from the OSCAR project) and by spreading knowledge through platforms like Agricology (15) .

12. AgroDiversity Toolbox (uni-kassel.de)
13. OSCAR Cover Crop Database (uni-kassel.de)
14. vm193-134.its.uni-kassel.de/toolbox/DST.php?language=English
15. www.agricology.co.uk

2.5 Effective termination of cover crops; without herbicides; impact on following crop

In this report we will use the general definition of cover crops proposed by Woolford and Jarvis (2017): cover crops are grown for protecting or improving something on the farm between regular crop production (usually autumn/winter). Catch crops are a subcategory of cover crop grown for a short period of time, i.e. a fast-growing crop that can be grown between successive main crops to provide soil cover, organic matter, rooting structure and in certain circumstances provide some livestock grazing (usually 6-10 weeks); we would add that they are also grown to "catch" excess soil nutrients following a main crop.

Topics 2.5, 2.6 and 2.7 all relate to the use of cover crops in regenerative agriculture. Cover crops have been studied for many years in the UK. Between 1989 and 1993 17 experiments were conducted in a BBSRC-funded project that tested a range of cover crop types following cereals or oilseed rape (Allison et al. 1998); one interesting finding from this work was that volunteer cereals and weeds in many cases produced as much biomass and captured as much N as sown cover crops. Defra funded several projects in recent years related to cover cropping (see Table 4 for a listing of some of these). More recently, there have been several projects that have addressed some of the practical issues relating to the integration of cover crops into arable cropping systems in the UK. The Cover Crops Guide(16) project (a Defra Farming Innovation Programme project completed in 2023) provides up-to-date information on challenges 2.5, 2.6 and 2.7 with links to a further 16 online resources(17) (websites, reports, and decision support tools) with practical information on the use of cover crops in the UK. It should be referred to for a more detailed assessment of the current knowledge and recommendations for cover crop use in the UK. For peer-reviewed information, the final report on Maxi Cover Crop (Bhogal et al. 2020) includes a literature review that is comprehensive and relatively up to date that can be referred to for more detail on state-of-the-art understanding of cover crops in the UK.

16. https://www.covercropsguide.co.uk/

17. Resources - Cover Crops (covercropsguide.co.uk)

This review updates a previous review conducted by White et al. (2016) and published by the AHDB. A peer-reviewed synthesis of cover cropping in temperate cereal production systems has also just been published by Fioratti Junod et al. (2024) which provides an extensive analysis of the impacts of cover cropping on over 100 parameters relating to crop production and ecosystem service delivery. In addition to the results reported in this study, its reference list also provides a useful listing of all recent publications on cover crops in temperate systems.

We used three terms to search for peer-reviewed papers under the umbrella of "cover crops", this included cover crop as well as green manure (sometimes used to refer specifically to a cover crop grown to build soil fertility) and catch crop.

Methods for termination of cover crops have been raised as a possible gap in knowledge during this review. The majority of conventional regenerative farmers who use cover crops rely on glyphosate for termination of cover crops prior to direct drilling of their crops; there are concerns about the impacts of this herbicide on ecosystem health as well as a realisation that regulations may limit its availability in the future (Storr et al. 2021). There have been over 500 papers published that discuss methods for termination of cover crops; the first 50 of these (ordered on Web of Science by relevance) were manually screened and 20 selected that were particularly relevant to this challenge. These report on a range of termination methods including: roller-crimper (Ciaccia et al. 2016; Jani et al. 2016), herbicide (usually glyphosate), discing/cultivation/undercutting

(Wortman et al. 2012; Jani et al. 2016), grazing (Herremans et al. 2021), haying/harvesting, frost (Storr et al. 2021; Gabbrielli et al. 2022b, a), and flailing (Woolford and Jarvis 2017).

Organic farmers face challenges with terminating cover crops since they can't use a herbicide; studies in organic systems can offer useful insights into the best approaches to reduce reliance on herbicides. Studies from the United States indicate that some cover crops can be terminated effectively my flailing or using a roller-crimper (Carrera et al 2004 reported in (Wayman et al. 2015)). Cereal crops (e.g. rye) appear to be particularly suited to roller-crimping if they are at the correct growth stage (early milk stage in rye). A PhD study at Newcastle University tried to replicate these systems in the northern UK climate; termination with an early maturing rye was conducted in late June and a high biomass was achieved with an effective kill of the rye. However, this is too late for establishment of a spring sown arable crop and requires integration into a system where a fast-growing vegetable can be planted in order to make economic sense (Sonia Lee, unpublished).

Price et al. (2019) also looked into organically acceptable herbicides applied following roller/crimper termination e.g. a 20% vinegar solution, a cinnamon oil/clove oil mixture(18), a solarisation method that involved a clear polyethylene sheeting covering the plot for 28 days, and flame weeding over the entire plot area(19). The vinegar and cinnamon oil methods were not successful, but solarisation and flame weeding showed some promise.

Farmers in the UK may benefit from systems that use frost as a mechanism for termination of cover crops. This is used effectively in countries with colder winters where cover crops may be selected for their potential to frost kill e.g. as described for buckwheat in Wortman et al. (2012). Storr et al. (2021) explored the potential of using a mixed species cover crop (60% black oats, 35% oil radish, 5% white mustard) that was planted in late August in Cambridge, UK after wheat harvest. The cover crop growth was inhibited by the frost, but glyphosate was still required to completely terminate it before establishment of maize in the spring. Howard (2016) suggests crimson clover as a

18. 45% cinnamon (Cinnamomum verum L.) oil (cinnamaldehyde, eugenol, eugenol acetate)/45% clove oil (eugenol, acetyl eugenol, caryophyllene)

19. broadcast flame emitting 1100oC applied at 1.2 k/h (flame)

legume that is frost-sensitive so may not survive the UK winters. Phacelia is recommended in the NIAB TAG Cover Crops guide (NIAB-TAG 2016) as a frost-sensitive cover crop that would be suitable in mixes where winter-kill is desirable. In all of these cases the benefits of cover crop kill will need to be weighed against the added risk of nutrient release (particularly nitrogen) during the winter which may increase N leaching (Storr et al. 2021). Finally, some farmers are experimenting with using roller-crimpers to mechanically destroy cover crops during periods when the ground is frozen; as yet there is no clear evidence on the efficacy of this approach.

An Innovative Farmers project: Alternative methods for terminating cover crops [20] explored this topic, but treatments were not replicated and results were not conclusive. Some ongoing projects will include treatments that explore alternative methods for terminating cover crops (Table 2); outcomes of these should be monitored.

Table 2 Ongoing projects that explore alternative approaches to terminating cover crops

Project	Website
Centre for High Carbon Capture	https://www.niab.com/research/agronomy-and-farming-systems/centre-high-carbon-capture-cropping
New Farming Systems (NFS) Project	https://www.niab.com/research/agronomy-and-farming-systems/research-projects-agronomy-farming-systems/new-farming-systems
Large-scale Rotation Experiment	https://www.rothamsted.ac.uk/news/new-long-term-experiments-rothamsted-will-shed-light-potential-impacts-regenerative

Exploring mechanical methods of terminating cover crops is crucial for reducing reliance on glyphosate. This area is a high priority for applied research. However, environmental conditions in the UK may pose challenges for implementing certain alternative methods, such as roller-crimpers. Therefore, there is a need for applied, on-farm research across various UK environments and with different cover crop species to identify the most suitable termination methods. Additionally, selecting or breeding cover crop varieties with early maturity to facilitate mechanical destruction could be a key target.

20. https://innovativefarmers.org/field-labs/alternative-methods-for-terminating-cover-crops/

2.6 Regional adaption of cover crops: particulary for cool, wet temperature climates

The UK, particularly in the north, can be a challenging environment to implement cover cropping systems. Arable crops like wheat, beans and oilseed rape, as well as potatoes, are often harvested later in the year (after 1 September) which makes the window for good establishment of a cover crop over the winter relatively small. Bhogal et al. (2020) recommend establishment by the end of August for biomass production, root development and nutrient uptake. There is a need for the development of cover cropping systems that are adapted to these short seasons and that will grow well in the cool, wet weather that is common in the UK in autumn and winter. The development of cover crop varieties that are suitable for UK environments (climate and soil types) was listed as one of the top priorities for research by White et al. (2016). They recommended the characterisation of existing varieties based on disease & pest susceptibility; rotational effects; the suitability for different environments; suitability in different mixes; rooting capacity; and biomass production, with a recommended list for cover crops produced.

Very few academic papers have been published on factors affecting cold tolerance of cover crops. Moore et al. (2020) in the Journal of Plant Registrations, reported on the process used to develop and register two varieties of hairy vetch (Purple Bounty and Purple Prosperity) that were early flowering and had adequate winter survival, for use in organic systems. Baresel et al. (2018) described a specialised breeding programme in Germany for selection of varieties of subterranean clover that will survive the German winter. Both of these examples illustrate the potential to use crop breeding approaches to optimise cover crop varieties for specific uses and locations; something that is not yet being done to any major extent by seed companies in the UK.

Cover crop mixtures have been proposed as another strategy to build resilience into a cover cropping system. Species in the mixture may be adapted to different climatic conditions and broaden the range of environments where the mixture can survive and

and thrive. Vann et al. (2019) screened a range of legumes and small grains in mixtures as cover crops at several sites in the southern US and noted a wide variation in response depending on the location: they highlighted the importance of site-specific recommendations for cover crop species mixtures depending on the location.

Considering climate and soil types, evaluating and selecting cover crops (and varieties) well-suited to UK environments is a top priority for transitioning to regenerative agriculture. There is significant potential to select from within the pool of existing crop varieties with a focus specifically on their role as cover crops to tackle this challenge. Collaborative efforts including facilitated knowledge sharing between farmers and seed houses are recommended.

2.7 Impacts of cover crops on weeds, pests and diseases

Cover crops can suppress pests (insects and disease) as well as weeds through the release of chemical compounds. This may include allelopathic(21) effects on weeds during cover crop growth or post termination. McKenna et al. (2018) summarise the evidence of allelopathic impacts of red clover highlighting the possible mechanisms including the release of phytoxic compounds like phenols and isoflavonoids by the roots and residues. They also point out the potential for breeders to select cover crops for allelopathic effects if the mechanisms can be identified; as mentioned above, this highlights the huge potential to develop cover crop breeding programmes relating to key functional traits like allelopathy. The cover crop report produced by the Game and Wildlife Conservation Trust (Woolford and Jarvis 2017) goes into some detail on practical approaches to using cover crops to suppress weeds.

Cover crops may also release compounds after the cover crop is destroyed that are toxic to pests or inhibit their reproductive cycles. The most well-known example of this in the UK is the use of Brassica cover crops (e.g. Brassica juncea, Raphanus sativus and Sinapis alba as cited in Doheny-Adams et al. 2018) for biofumigation in potato rotations. In these systems the cover crop is incorporated into the soil where it releases isothiocyanates that suppress potato cyst nematodes (Lord et al. 2011). These systems have been researched extensively with species like Brown mustard marketed for their action against pests and pathogens like PCN, Pythium, Rhizoctonia and Verticillium (e.g. by Boston Seeds)(22) . The toxic compounds released during biofumigation may present a risk to beneficial soil organisms; however, research by Wood et al. (2017) indicated rapid recovery of soil functions and no lasting effects on soil microbial communities from biofumigation.

As well as positive effects from cover crops, there may also be negative effects on subsequent crops. Cover crops grown between cash crops in rotations may act as a "green bridge" hosting disease and insect pests that can become a problem in the

21. Allelopathy is the chemical inhibition of one plant (or other organism) by another, due to the release into the environment of substances acting as germination or growth inhibitors

22. https://www.bostonseeds.com/products/forage-crops/brown-mustard/

following crop (see Woolford and Jarvis 2017 for more practical suggestions on ways to reduce this risk). Weed suppressing action of cover crops may also inhibit growth of the subsequent cash crops. Both of these mechanisms may be the reason that a cover crop of a cereal is not recommended when the subsequent crop is another cereal, as demonstrated in the Maxi Cover Crop project where a cereal cover crop (oats and particularly rye) negatively affected rate of crop establishment, rooting depth and ultimately grain yield of a subsequent spring barley crop (Bhogal et al. 2020).

The impact of cover crops on disease, pests and weed pressure in subsequent and surrounding crops has been relatively little studied and is a high priority area for research. There may be an opportunity to select cover crops to reduce pest pressure; examples already exist for beet cyst nematode. The role of cover crops for weed suppression, particularly blackgrass, is less well understood, as emphasized by Andy Cato at the Future of Agriculture conference.

Allelopathy, which involves the chemical inhibition of one plant (or other organism) by another, is a crucial area of research in regenerative agriculture. Designing systems that leverage allelopathy through integration of cover crops within crop rotations to support pest and weed control will be essential for reducing reliance on pesticides. Both fundamental and applied research are needed in collaboration with farmers to bring together understanding of mechanisms of allelopathy and build from farmer experience. While blackgrass control could be prioritized, other weeds (e.g. sterile brome) and pests (e.g. wireworm) should also be considered based on farmer interest. Supporting evaluation and selection of cover crops to optimize allelopathic traits is important for advancing this approach.

2.8 Reducing herbicide use in regenerative systems

As discussed in challenge 2.5, there is a reliance on herbicides in systems with reduced tillage and a concern that this remains a weakness for many regenerative farmers. A Web of Science search identified just 12 papers that dealt directly with this issue in regenerative agriculture.

Bloomer et al. (2024a) provide an up-to-date review on non-chemical weed control methods including electrical weeding technologies. These methods are included in an ongoing European Innovation Action: Oper8(23) which is compiling a large database of knowledge exchange materials on alternative weed control methods; many of these will be suitable for regenerative systems.

A novel approach to reducing the use of conventional herbicides is to optimise microbial function to suppress weed growth. Cheng et al. (2022) review these approaches that include: "(1) identifying soil microorganisms that inhibit weed growth; (2) discovering microbial natural products that suppress weeds; and (3) developing field management approaches that promote weed suppression by enhancing soil microbiome function." The latter approach, which may be termed "weed suppressive soils" is gaining interest in the regen ag farming community, especially among farmers who are monitoring and managing soil bacterial and fungal populations. There is currently little evidence that these methods work in practice. More fundamental research is needed to gain a mechanistic understanding of the processes involved (see Challenge 4.2 for more discussion on the role of soil biology in weed suppression); this research would be strongly linked to the allelopathic research needs relating to cover crops in rotation mentioned above.

Reductions in herbicide use will ideally be an outcome of the system redesign that is part of the transition to regenerative farming practices. Integration of more diverse rotations and cover crops, will help to suppress weeds. Wacławowicz et al. (2023) explored multiple factors associated with regenerative systems in a field trial with spring barley and emphasised the importance of practices which enhance barley

23. https://www.oper-8.eu/about/

growth and competition with weeds (e.g. adequate supply of nutrient via N fertilisation).

The new Large-scale rotation experiment at Rothamsted(24) (Li et al. 2023) will include monitoring of weed populations under a “smart crop protection” regime that does not eliminate herbicides but aims to reduce their use through integrated pest management approaches. Detailed monitoring of weed populations and pressure in this experiment should provide valuable insights into the impacts of a range of practices on weeds.

Since 2000 there have been several projects on weed management funded by Defra (Table 3) that should be reviewed to inform future research activities around strategies to reduce reliance on herbicides in regenerative farming systems.

Table 3 Summary of projects funded by Defra relating to weed management

Title	Completion Year
Modelling weed crop dynamics and competition to improve long-term weed management - AR0407	2005
Sustainable weed management: development of techniques to balance biodiversity benefits with retention of yields - AR0408	2005
Parameterising the biology and population dynamics of weeds in arable crops to support more targeted weed management - AR0409	2005
Modifying weed management in a broad row crop (maize) for environmental benefit - AR0412	2004
Improved management of grass weeds in cereals - CE0612	2001
The integration of mechanical and chemical weed control in winter cereals - CE0614	2001
Integrated weed management in winter cereals - mechanical weed control - CE0615	2001
Weed competition and crop canopy manipulation in winter wheat - CE0616(4)	2001
Improving crop profitability by using minimum cultivation and exploiting grass weed ecology. - LK0923	2005

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

New programs should build on the knowledge developed in past projects funded by Defra on mechanical weed control. This challenge was identified in discussion at the workshop and is recognised as being a key driver for many of the challenges above, such as cover cropping, living mulches, and allelopathy. Additionally, a deeper understanding of how the soil/plant microbiome may influence processes that suppress weeds may allow new approaches (see Challenge 4.2). While this area holds promise, more fundamental research would be needed before recommending soil microbiome manipulation in the field.

2.9 Integration of livestock into arable regen systems

A key principle of regen ag is the integration of livestock into the farming system(25) . This usually refers to the reintroduction of ruminants into arable systems through the inclusion of a ley phase in an arable rotation (ley-arable option described in Jordon et al. 2023) but could also include monogastrics like pigs or chickens rotated on arable land and/or their manure being used as an input to an arable cropping system.

The recent review by Burgess et al. (2023) for Defra includes a rapid evidence assessment of the impacts of integrated crop-livestock systems where livestock are added to crop systems and vice versa. They identified the location of studies as a problem with most of the papers reviewed from outside of Europe; they also reported a lack of replicated comparisons of integrated and specialised systems in UK and the rest of Europe.

The benefits of manure use on cropland are well documented and there is a large body of historical information about how to use manures as nutrient sources on cropland. Improvements in recommendations i.e. in RB209 could be a piece of applied research, building on new technologies in precision application of organic manures, that would support the transition to re-integration of livestock into cropping systems. The Organic Research Centre is currently conducting a comprehensive review of composting methods that will identify knowledge gaps and future directions for research in organic waste management(26) . This will inform a developing research programme at ORC on "balancing nutrient cycles for resilience".

From the farmer's perspective the challenges of integrating livestock into cropping systems may be logistical i.e. with housing, fencing, and provision of water, or relating to knowledge i.e. a lack of experience and know-how about livestock production among arable farmers. These barriers will be discussed further in Challenge 6.2.

25. In this report we will use the term "integrated crop-livestock systems" or "mixed farming systems" to refer to systems where the crops and livestock are integrated within the same farm business and "coupled crop-livestock systems" to refer to systems that maintain on-farm specialization but utilize neighboring farms to manage system inputs effectively (e.g., muck-for-straw deals) (Cooledge et al 2022).

26. https://www.organicresearchcentre.com/our-research/research-project-library/feedthesoil/

From a policy perspective, there are concerns about the environmental impacts of livestock in arable farming systems. While the soil health benefits of ley phases are well recognised (Berdeni et al. 2021; Cooledge et al. 2022), systems with high densities of livestock on the land, particularly when soils are at field capacity(27) or above, can create environmental risks. The University of Leeds has an outdoor pig system where the land is rotated with arable crop production (Pun et al. 2024). They have observed reductions in soil carbon in the upper soil layers in pig pastures as well as an accumulation in available nutrients that could present an environmental hazard.

Outwintering has become increasingly popular among cattle farmers, but it can also increase risks of environmental damage. A modelling study (McGechan et al. 2008) simulated significantly higher risks of phosphorus and ammonium pollution of water around fields where cattle were outwintered. Barnes et al. (2009) conducted workshops with farmers who practice outwintering and found that farmers are also concerned about possible negative impacts on soil health and runoff of nutrients, as well as public perceptions about animal welfare(28). Further research is needed to ensure that systems that integrate livestock into arable rotations do not result in negative environmental or animal welfare outcomes.

Trickett and Warner (2022) reported on a farm study where earthworms were counted in fields managed with zero tillage, with and without mob grazing. They found significantly higher numbers of earthworms where grazing was included, speculating that the diversity of carbon sources in grazed systems promotes earthworm numbers. Sheffield University’s project: Restoring soil quality through re-integration of leys and sheep into arable rotations (2019-2022) addressed a variety of questions including: “Does soil quality improve faster using mown rather than sheep-grazed leys and how do they compare economically and in terms of wider ecosystem service benefits such as reduced flood and pollution risks?”.It is challenging to include grazing in replicated field trials due to the logistics of providing fencing and water, so this project was unusual and provides some valuable insights into the impacts of livestock grazing on herbal leys (multispecies swards) compared to grass-clover leys. No differences in

27. Field capacity is the water content above which any additional precipitation drains out of the soil profile; typically soils during the winter months are at field capacity.

28. This was part of a Defra project: 'Identification and mitigation of the environmental impacts of out-wintering beef and dairy cattle on sacrifice areas' (contract no. SFFSD 0702)

soil health parameters were detected between the two species mixtures when they were both grazed; they also reported significant declines in some of the key species in the herbal leys after just two seasons of grazing (Cooledge et al. 2024). This is something that also has been reported anecdotally by farmers that use these mixtures (see various posts on social media). Management for persistence of herb species in herbal leys remains a challenge. The final recommendations from this project are worth repeating here:

> Further research is needed to explore the best practices to establish and maintain optimal functional diversity in herbal leys to deliver the promised ecosystem benefits given the growing popularity of herbal leys in agri-environment schemes. Long-term national-scale studies are needed to assess the impact of herbal leys compared to grass or grassclover leys on soil quality, capturing variations in soil mineralogy, field and grazing management, sward composition and age. Overall, we can conclude that the additional costs to farmers utilising commercial herbal leys (with a typical seed cost of ca. £200–250 ha–1) compared to grass-clover leys (ca. £150 ha– 1) is not currently rewarded through the delivery of greater below-ground ecosystem services observed during this 2-year study. Instead, further refinement of herbal leys is needed prior to wide-scale adoption, as currently conventional grass-clover leys provide equal ecosystem benefits. (Cooledge et al 2024)

Other relevant projects include ADAS’s “Mob grazing: Impacts, benefits and trade-offs”(29) which is a comprehensive assessment on the impacts of mob grazing versus rotational and set stocking systems; this study has relevance to farmers needing information on the pros and cons of different grazing management systems. SRUC’s long-term Tulloch organic rotation trial(30) has been running since 1991 and includes grazing sheep as a factor; it should also be reviewed to synthesise lessons learned to inform future research projects.

29. https://adas.co.uk/services/grassland-and-forage-research/

30. https://glten.org/experiments/304

A central tenet of regenerative agriculture is the integration of livestock into the farming system. This challenge was identified in discussion at the workshop. The issues associated with this challenge primarily revolve around practical barriers, such as housing, fencing, providing water, and access to livestock vets and abattoirs, as well as a lack of experience and know-how about livestock production among arable farmers. This challenge could be tackled by documenting the lessons learned by farmers who have successfully re-integrated animals into their systems through case studies; AHDB have a useful set of resources available(31)**.**

31. https://ahdb.org.uk/livestock-and-the-arable-rotation#:~:text=manure%20and%20more.-,Why%20incorporate%20livestock%20in%20the%20arable%20rotation%3F,particularly%20those%20identified%20as%20underperforming

2.10 Design of locally-adapted crop rotations for regenerative systems

Numerous academic studies have looked at crop rotations (over 25,000 papers on Web of Science) and 39 of these specifically refer to regenerative agriculture. The 39 regenerative agriculture-focussed studies were rapidly reviewed and some findings are reported here, along with results from recent project reports.

The general benefits of rotating crops where different crops are grown in sequence on the same arable land is well understood and documented. Most recently, Burgess et al. (2023) covered the benefits in their report to Defra "Evaluating Agroecological Practices". They focused their discussion on the inclusion of break crops in arable rotations(32) and reported benefits including: increased soil organic carbon, microbial diversity and diversity in general, yield(33), and sometimes greenhouse gas emissions. They highlighted the need to increase the usability and gross margins of the "break crops" to improve rotational profitability.

But rotations can also include ley phases (see 2.9 Integration of livestock into arable regen systems) and cover crops (see sections 2.5 to 2.7). Rotations that maximise the benefits of these additional components need to be developed. There is some emerging new thinking on how diversity in agroecosystems can be managed to improve efficiency of nutrient supply and productivity (e.g. Fontaine et al. 2023). A new framework for studying rotations that incorporates some of these concepts e.g. design of rotations to optimise plant–soil synchrony needs to be developed, in the context of longer (perennial) and more complex rotations.

Impacts of diverse rotations, particularly on soil health and resilience, need to be better understood. "Perennialisation" of crop rotations, i.e. the inclusion of more perennial crops such as grass-clover leys, can have positive effects including the moderation of microbial processes that lead to stabilisation of newly added residues. McDaniel et al. (2023) found that diversifying and extending the duration of living plants in rotations

32. Crops grown to break disease cycles in main crops, e.g. oilseed rape is a common break crop in cereal rotations. Peas and beans also serve this function.

33. At the level of the individual crop; yields across rotations expressed in a standard unit, e.g. calories ha-1

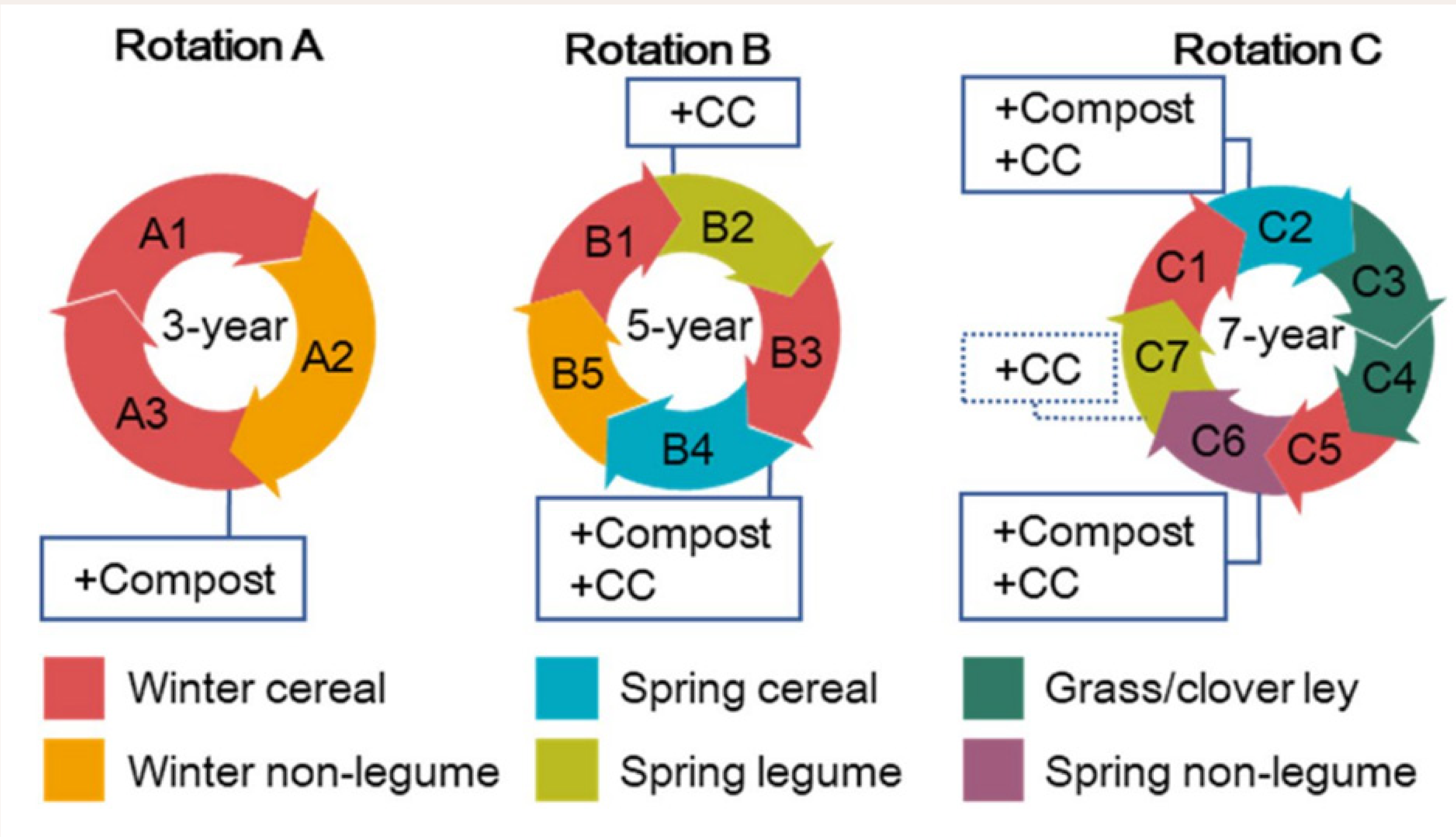
lead to greater retention of new residue inputs. These effects were also studied by Mooshammer et al. (2022) who suggested enhanced stabilisation of microbial-derived soil organic matter (SOM) and functional shifts in the microbial community as a common mechanism for positive effects of diverse rotations on SOM dynamics.

In general, rotating crops enhances microbial (including bacterial, fungal and archaeal) diversity but the molecular techniques most commonly used in these studies do not provide insights into how this diversity affects agroecosystem functioning (Venter et al. 2016). Future studies should measure more direct indicators of soil function in parallel with studying taxonomic diversity to verify if greater diversity really does lead to enhanced soil functions (see Challenge 4.1 Better indicators of soil biological function).

An exciting and important avenue for research in the UK lies in the design of diverse rotations that balance provision of multiple ecosystem services with food production and that consider impacts of regenerative rotations on the wider food system. Food system impacts and research needs will be explored further in Challenge 5. The new Large-Scale Rotation Experiment (LSRE; Li et al. (2023); Figure 2) will provide a valuable platform for studying the effects of diverse rotations on a range of outcomes at the field and farm scale, including agronomic (productivity and nutritional quality), environmental (soil health, resource use efficiency, losses to the environment and biodiversity) and economic (inputs and farm profitability). This will provide evidence and data to parameterise more advanced cropping and farming system models that can be used to simulate a range of future rotational designs and their impacts on outcomes. While there are a variety of crop models already in existence (e.g. DSSAT, STICS, APSIM) none of these are able to effectively simulate regenerative innovations in crop rotations such as cover crops, living mulches and intercrops. The development of the next generation of crop models that can include these innovations is a research need that could hasten the design and testing of new rotations for UK regenerative farms.

Accurate prediction of the dynamics of N supply over the rotation will be important for efficient rotation design. Cover crops are a key component of regenerative rotations and they can capture and release N to the following crop (Heuchan et al. 2023); likewise, legumes grown as short term green manures or in long-term ley phases, can provide significant amounts of N to the crops in the rotation. But there are still challenges with estimating the quantities and timing of N released by cover crop and leguminous residues to subsequent crops in the rotation. Improving predictions of supply to crops from organic nutrient sources remains an important area of research.

Figure 2 Diagram copied from Li et al (2023) that illustrates the 3, 5 and 7 year rotations included in the new Large-Scale Rotation Experiment established by Rothamsted Research at two sites in the UK



Various projects already mentioned(34) have covered crop rotations including innovations like intercropping and living mulches. In addition, the Defra projects listed in Table 4 all have some relevance to the design of crop rotations and should be taken into consideration when planning future research on rotations. Burgess et al. (2023) identified a gap in evidence relating to the profitability of break crops and recommended more research to increase the usability and gross margins of break crops e.g. grain legumes .

34. Diversify - Designing Innovative plant teams for ecosystem resilience and agricultural sustainability; Optimising Subsidiary Crop Applications in Rotations (OSCAR); Sustainability Trial for Arable Rotations (STAR); Centre for High Carbon Capture; New Farming Systems (NFS) Project; Restoring soil quality through re-integration of leys and sheep into arable rotations; Large-scale Rotation Experiment

This challenge revolves around designing rotations tailored to specific contexts, considering the environment and farming system. Achieving this will need on-farm, collaborative research approaches that link together theoretical understanding from past research and empirical observation in real-world situations. Not all local combinations of soil-climate-farm situation will be able to be studied, hence a multidisciplinary approach linking modelling and observation will be essential, taking into account both environmental and economic impacts of rotation design. This challenge was identified in discussion at the workshop, and the need for such work supported by discussion at the Future of Agriculture conference. Any successful research will also require applied, on-farm testing alongside knowledge exchange activities. Various groups, such as AHDB, ORC, NIAB, and the Soil Association, possess the expertise and networks to deliver this type of project effectively.

Table 4 Summary of past Defra projects that may include information relevant to design of crop rotations for regenerative agriculture

Project	Completion Year
To prepare guidelines on the use of cover crops to minimise leaching NT1508	1995
Utilising N in cover crops - NT2302	1999
Optimisation of nitrogen mineralisation from winter cover crops and utilisation by subsequent crops. - OF0118T	2000
The contribution of cover crops incorporated in different years to nitrogen mineralisation - NT1526	1999
The effects on weed seedbank depletion of cover crops, fallowing and - PS2724	2013
DTC Phase Final Report	2019
The development of national guidelines for sustainable soil management through improved tillage practices - SP0513	2001
CORE 2: Reduced tillage and green manures for sustainable organic cropping systems	2014
Modelling weed crop dynamics and competition to improve long-term weed management - AR0407	2005
Sustainable weed management: development of techniques to balance biodiversity benefits with retention of yields - AR0408	2005
Parameterising the biology and population dynamics of weeds in arable crops to support more targeted weed management - AR0409	2005
Modifying weed management in a broad row crop (maize) for environmental benefit - AR0412	2004
Improved management of grass weeds in cereals - CE0612	2001
The integration of mechanical and chemical weed control in winter cereals - CE0614	2001
Lupins in Sustainable Agriculture - LISA - LK0950	2009
The incorporation of important traits underlying sustainable development of the oat crop through combining conventional phenotypic selection with molecular marker technologies - LK0954	2009

2.11 Design of equipment for regen systems

The need for specialised equipment to facilitate the transition to regenerative farming systems was raised at the stakeholder workshop as an additional challenge. The development of new types of equipment to meet the needs of the farming community is not unique to regenerative agriculture: but some specific needs can be identified. These include:

1. Seed drills suited to no-till establishment of crops; there are many already on the market (the latest models are normally demonstrated at regen ag events like Groundswell every year). Equipment manufacturers continue to develop improved systems to address challenges with direct drilling including dealing with high crop residue levels and problems with slot closure (particularly in heavy soils). The type of research needed to address problems with seed establishment in no-till systems is applied research on farms across a diversity of cropping systems and soil types. Case studies and documentation of successful drilling systems including details on models of seed drills used would help to reduce the amount of trial and error currently happening in the sector to determine the best drill for a specific context.

2. Equipment that can reduce reliance on herbicides for weed control in no-till systems is a need relevant to the whole arable sector, but may be particularly important for regen farmers who don’t use tillage. Some research relevant to this topic is already outlined in section 2.8. The Oper8 project has a large, searchable database of technologies and practices to reduce reliance on herbicides; this includes techniques that minimise soil disturbance like precision application of herbicides and electrical weeding. Bloomer et al. (2024b) recently published a paper demonstrating the efficacy of flat-plate electrode weeding equipment applying ultra-low-energy electric shocks to control weeds in the field.

3. Integration of livestock into arable systems remains a challenge for farms that don't have infrastructure to manage grazing animals (see section 2.9). Innovative fencing systems including Nofence(35) collars can offer a solution for cattle grazing, but costs of these systems may be prohibitive; they also are not suited to sheep systems. The industry itself is constantly innovating to develop novel electric fencing systems that minimise labour requirements. Close collaboration with fencing manufacturers and graziers (particularly those using mob grazing methods) should be encouraged to identify the key challenges and co-create solutions. Case studies of arable farmers who have successfully integrated grazing animals into their systems would be valuable to increase transfer of knowledge on best practice among the regen ag community.

4. Regenerative farmers are particularly interested in the use of novel products such as compost teas and biostimulants. Equipment that simplifies the development of improved composting methods is needed including compost turners that effectively mix and aerate the pile without high inputs of energy and systems for passive aeration of compost piles on a larger scale than the typical Johnson-Su bioreactor. For application of compost teas sprayers may need adapting since typical sprayers are low volume-high pressure systems that may not be suited to the rates of application and composition of compost teas.

This project did not set out to document all the possible equipment development needs of the regen ag sector. A first step to develop a programme in this area should be to convene a workshop with some of the key research institutions working on these topics (Lincoln University, Harper Adams University) and industry stakeholders, as well as equipment manufacturers, to identify key needs and a roadmap forward. The current Defra Farming Innovation Programme is well suited to fund development of novel equipment to meet the needs of the sector.

35. https://www.nofence.no/en-gb/

Equipment design, especially the challenge of obtaining smaller-scale equipment to encourage the adoption of regenerative agriculture on small farms and in market gardens, was highlighted by the stakeholder workshop. At larger scales, there’s a need for adaptation of current equipment to enable the implementation of multi-species cropping systems, such as combines for harvesting intercrops, drills for planting into living mulches, flails/roller-crimpers for terminating cover crops, and seeders for planting cover crops into standing crops. Meeting this challenge will need collaborations between farmers, equipment designers, and manufacturers.

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

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