Rapid Evidence Assessment to Map UK crop science research with a Regenerative Agriculture focus

D2: A summary of key knowledge gaps, research needs and ways to address them

Final report incorporating stakeholder workshop & outcomes from the Future of UK Agriculture Conference

July 2024

Julia Cooper, Organic Research Centre
Elizabeth Stockdale, NIAB
Belinda Clarke, Agri-TechE

With funding from Aurora Trust, The Mark Leonard Trust and the Gatsby Charitable Foundation

Table of Contents

Contents

List of Tables

List of Figures

1 Introduction

The first phase of this project involved a rapid review of information and key research findings/knowledge gaps on regenerative agriculture in the UK; part of this process included the construction of a database listing key individuals, organisations, projects and reports in the UK that have a regenerative agriculture focus (i.e. that included reference to regenerative agriculture in the title, abstract or project description). This database has been updated throughout the project as new information is constantly being sourced; the final version of the database (without personal contact information) can be requested from the authors of this report.

The list of topics presented at the workshop were framed as knowledge gaps; however, during Phase 2 it became apparent that some "gaps" were not really gaps in knowledge i.e. there was already a wide body of knowledge available on this topic. We therefore have reframed this list as "challenges".

Phase 2 of the project included an online workshop where invited experts amended/refined and scrutinised the knowledge gaps (challenges) identified in Phase 1. The outcomes of this process are reported below. These formed the basis for a detailed review of the evidence currently available on each of these challenges. Based on the outcomes of the review of evidence, an assessment was made for each challenge, which indicated the current body of evidence on that topic and informed proposed future activities to address that challenge (e.g. meta-analysis of published information, synthesis of existing information, translation of scientific results into guidance, further experiments etc).

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) that the Committee on Climate Change commissioned to assess the role of agroecological farming in the UK transition to Net Zero. They focused on nineteen agroecological farm practices (AEFPs) grouped into six categories: reduce soil disturbance, organic inputs, diverse crop rotations, multifunctional land use, pasture productivity and livestock extensification. While they did not explicitly refer to "regenerative agriculture" in their review, the practices listed above are all advocated within the regenerative movement.

Figure 1 Summary of the outcomes from the rapid evidence review on agroecological farming practices (Albanito et al. 2022)[z]

System	AEFP	GHG	C stocks	Production	Co-benefits	AEP addressed	Integration
A	No-till - Minimum tillage	🔴	🟢	🔴	5	3	High
A	Perennial cereal crops		⚪	🔴	11	5	Low
M-L	Pasture cropping		🟢	⚪	8	3	Low
A	Liming*		🟢	🟢	5	3	High
A	Retention of straw	🔴	🟢	🔴🟢	11	3	High
A-M-L	Organic manure	🔴	🟢	⚪	5	2	Medium
A	Cover crop	🔴	🟢	⚪	17	6	Medium
A	Intercropping			🟢	12	5	Low
A-M	Legume crops		⚪		11	6	Medium
A	Ley-arable		🟢	⚪	11	5	Low
A	Silvoarable	⚪	🟢	🔴⚪	6	2	Low
M-L	Silvopasture		🟢	🟢	10	4	Low
A-M-L	Vegetated strips	🟢	🟢	🟢	17	5	Low
M-L	Rotational grazing		🟢	🟢	12	6	High
M-L	Multispecies leys		🟢	🟢	12	5	Low
M-L	Extensive grazing	🔴	🟢	⚪	9	4	Low
M-L	Grass-based diets	🔴🟢⚪	🟢		2	1	Low
M-L	Permanent pasture		🟢	🔴	10	3	Medium

[z] *Summary of the number of co-benefits (positive effects) and trade-offs (negative effects) generated from the implementation of different agroecological farm practices (AEFP) across arable (A), livestock (L) and mixed (M) farming systems. C stocks and Yield benefits and trade-offs are expressed with circle symbols for the indicator GHG emissions. Green, red and grey circles correspond to positive, negative and no effect. Empty cells indicate that insufficient information was available. More than one coloured circle reflects contrasting findings in the literature. Co-benefits show the total number of indicators with only positive effects. AEP summarises the agroecological principles addressed by each AEFP. The category Integration represents the level of use of each AEFP in today's agriculture, based on scientific knowledge and practical on-farm experience with practices.*

Figure 1 provides a useful summary of the outcomes of this study. In particular, it shows areas where there was insufficient information to draw conclusions. This is the case for the impacts of intercropping on GHG emissions and soil C stocks (intercropping is also identified in our study as an area with gaps in knowledge and evidence). The impacts of legume crops on GHG emissions and production also have insufficient evidence, as do perennial cereal crops and ley arable systems (GHG emissions only).

In late 2023, the outcomes of a DEFRA-commissioned study on the impacts of agroecological compared to conventional farming systems were published (Burgess et al. 2023). The project reviewed 16 agroecological practices, documented barriers and enablers to uptake of agroecological and regenerative practices and identified knowledge gaps and infrastructure needs. Crop rotations, conservation agriculture, cover crops, organic cropping, integrated pest management and integration of livestock with arable cropping were all included as agroecological practices within the project.

Most recently, the Agricultural Universities Council conducted an assessment of farmer priorities for research through a series of workshops (Crough et al. 2024). 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 (regen ag) in cropping systems, with a particular emphasis on soil health. This makes it slightly more focused than these other studies and the information gathered will complement the outcomes of these three recent studies.

2 Stakeholder workshop outcomes

The stakeholder workshop held on 7 February helped to prioritise the knowledge gaps and also to highlight some areas missing from the presented list. A brief summary of the workshop outcomes is included in Annex 1. Text comments provided on the workshop survey as well as summaries of the discussions in the breakout rooms were used to broaden the list of knowledge gaps (Annex 2 - Summary tables from survey and discussion during the expert's workshop)

Some really useful comments included:

- The prioritisation of knowledge gaps will very much depend on the types of stakeholders who are asked; farmers may have different priorities than fundamental researchers.
- There is a lot of misinformation out there, especially within the regen ag world; there is a need to support peer-peer practice sharing - but also a need to limit sharing of weak/incorrect science; this is a real challenge for the scientific community
- It is important to couple research and practice - but to ensure that farmers (or advisory groups who can act as the farmer voice) are appropriately recognised and rewarded
- The time frame is needed for context e.g. the priority knowledge gaps for the short-term (next one to two years) will not be the same as the ones that need prioritising for the next decade
- Regenerative agriculture is a relatively new movement/set of practices - there haven't been farmers using the regenerative suite of practices long enough in the

UK to make a good assessment of their impacts i.e. this would need methods to have been implemented for at least 5, but ideally 10-15 years

- We should look wider than the UK for studies to help us understand impacts of regen practices, e.g. in South America for studies on no till and min till
- There has been a lot of valuable research done in the past; we need to mine this work; such as crop rotations without synthetic input.

Some topics highlighted as missing from the gaps used in the survey were:

- **Tillage** and questions around impacts of no-till versus occasional/strategic tillage
    - there is good existing knowledge but more work is needed on applied research for local adaptation and KE to support adoption
    - how best to balance no-till and reduced herbicide use - is there an optimum which might mean no/strategic tillage approaches coupled to a more integrated sets of weed control practices?
- The impacts of increased **herbicide use** in regenerative agriculture systems (noting that there has been work done in other parts of the world on this) and/or how to reduce reliance on herbicide in reduced tillage systems
- **Agroforestry** and other multifunctional land uses
- **Equipment/robotics** - particularly the importance of smaller scale equipment to promote uptake of regen ag on small farms and in market gardens
- Questions and **challenges facing smaller-scale farmers** were not presented; the gaps identified seemed to be targeting large-scale farms, rather than horticultural or smaller operations; **root crops/horticultural crops** not really covered in the questions

There was a general feeling in the workshop that systems research is needed to develop regenerative agriculture; recognising that practice change on farms can have unexpected impacts on the whole food system. There was also a lack of gaps listed that could result in policy change, e.g. levers to influence farmer behaviour change, such as the effects of fertiliser N price on its use.

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. The reports and projects collated during phase 1 of the project were mapped onto these sub-challenges. The 34 sub-challenges were also the focus of a rapid search of academic literature (Web of Science) to identify peer-reviewed studies on these topics[1]. 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.

3 Challenges to implementing regenerative agriculture in the UK – current status of knowledge

Challenge 1: Standardisation of regenerative agriculture

1.1 Identification of metrics to support the definition

A major concern raised by researchers is the lack of a clear definition for the term "regenerative agriculture" which makes it difficult to conduct robust studies. Robert Rodale, son of the founder of the organic movement in the United States, coined the term "regenerative organic" in the late 1980s to refer to a holistic approach to farming that encourages continuous innovation and improvement of environment, social and economic measures (Sumption 2023), but the term was not widely used in the agricultural or scientific community until the 2000s. A literature search conducted during Phase 1 of this project identified just one article published before 1990 that used the term "regenerative agriculture"[2] and only two during the 1990s. The first time the phrase appears in the academic literature in a form similar to the commonly understood definition of the term, with direct reference to soil health, is in a conference paper published in the journal Applied Soil Ecology in 2000, that argues the need for a focus on soil health research for sustainable food production from relatively less land (Sherwood and Uphoff 2000).

Table 16 summarises the results of a Web of Science search of peer-reviewed literature conducted in March 2024, looking specifically for publications addressing the definition of the term. Globally there are 331 papers using the term regenerative agriculture, but only 18 of those cover definition, meaning or metrics. A further

---

[1] It is important to note that this rapid review of peer-reviewed literature may not include all papers on each topic; a selection were reviewed that represent the general state of peer-reviewed knowledge, with a focus on UK studies. A systematic review or meta-analysis would be appropriate to provide a more comprehensive review of a targeted question within each topic.

[2] All Web of Science searches used the TS category that includes article topic, title, abstract and author keywords

screening found 6 of those papers not relevant to definitions of regen ag, leaving 12 that cover this topic. These 12 papers represent a fascinating spectrum of perspectives on regenerative agriculture covering a range of disciplines. Most recently, Jayasinghe et al. (2023) published a review of definitions of regenerative agriculture. They identified a wide range of definitions reporting that it is a "framework consisting of principles, practices, or outcomes aimed at improving soil health, biodiversity, climate resilience, and ecosystem function". Their findings reflected those of Newton et al. (2020) who categorised definitions into two broad groups: those based on a set of practices and those that emphasise outcomes.

Jayasinghe et al. (2023) finally proposed a lengthy definition that recognises the importance of integrating knowledge of local landholders and indigenous people (see box to the right). While this is a highly inclusive definition, it lacks specific details necessary for distinguishing between different production systems in real-world applications. These specifics are crucial for gathering strong evidence about the effects of regenerative agriculture on the ecosystem services it aims to enhance.

RA is an agricultural and transdisciplinary approach that integrates local and indigenous knowledge of landscapes, as well as their management, with established scientific knowledge. It combines a range of adoptable principles with context-specific practices, focusing on soil conservation as the initial step to restore soil health, enhance ecosystem functions, and promote improved socioeconomic outcomes (Jayasinghe et al. 2023).

Sands et al. (2023) argue that the current debate which focuses on practices, principles and outcomes does not acknowledge the importance of social justice, relational values and the contribution of indigenous knowledge within regenerative agriculture. Page and Witt (2022) explain that the range of definitions and "competing discourses" is because regen ag has not "matured sufficiently for a clear definition to have emerged". Their study (although with a limited number of participants) is useful in identifying the different perspectives of farmers, some of whom dismiss regenerative agriculture as just another term for sustainable agriculture versus other groups who strongly identify with the term; interestingly, the regenerative group displays some scepticism towards science and technology while the other two perspectives (productive and environmentally conscious) see science and technology positively and agree that intensive agriculture is needed to feed the growing world population.

Various reports produced in the UK have also addressed definitions of regen ag, including Hurley et al. (2023), Burgess et al. (2023), Brunyee and Semple (2021), Magistrali et al. (2022) and Albanito et al. (2022). These have all focused on the practice or outcome-based definitions referred to above. The GREAT (Gloucestershire Regenerative Environmental Agricultural Transition) Project in South Gloucestershire, which offers support to farmers to transition to regenerative agriculture, summarised some of the pros and cons of defining regenerative agriculture (Table 1). They ultimately synthesised various definitions from global organisations into this definition:

> *Farming principles and practices that increase biodiversity, build better soils, improve water catchment and enhance nutrient cycling, with the aim of capturing carbon in the soil and increasing aboveground biomass; thereby helping to reverse the current global trends of atmospheric accumulation.*

Table 1 Benefits and disadvantages of an open definition for regenerative agriculture (Brunyee and Semple 2021)

Benefits	Disadvantages
● A regenerative system can be defined as an evolving and holistic mix of principles, practises and outcomes. ● It recognises that in differing climates, environments and soils, different practises can be used to achieve the same goal, or through adopting the same practise, results can occur at different speeds. ● It can flex to suit the farm, farmer or enterprise (the 6th principle), optimising outcomes. ● With the right information and tools, it can be adopted anywhere in the world. ● It grows from the bottom up.	● When the term is used within policy and strategy, the lack of a clear definition can result in lack of depth and/or focus, and ineffective delivery. ● A loose meaning can get lost and corrupted (watered down) over time. ● Regenerative claims can be mis-used, co-opted and overstated in marketing campaigns by farm businesses and associated industries i.e. green wash. ● Consumers may struggle to identify, understand and trust regenerative claims and brands. ● Researchers lack a clear framework or single-issue focus to follow when seeking evidence.

A general consensus from this review and discussions with stakeholders is that the preoccupation with defining regenerative agriculture is coming from the research community; actors along the supply chain who are benefitting from a loose definition of the term are not particularly eager to see it clearly defined[3]. However, when standards are discussed (see below) a clear definition of regenerative agriculture is viewed as essential (Elrick et al. 2022; Landers et al. 2021). Newton et al. (2020) also list a series of problems with the lack of a definition, including challenges for researchers trying to conduct comparative studies of systems, confusion among consumers, dilution or corruption of the value of the term over time, and difficulties

[3] This sentiment was articulated by Mike Gooding, Farming Systems Director, AHDB, in a meeting about this project

with developing laws, policies and programmes to evaluate and promote this type of agriculture.

The lack of a clear definition of regen ag limits the potential to conduct robust studies into regenerative agriculture systems; practice-based or outcomes-based definitions (with clear metrics to differentiate systems) are needed to design trials or surveys that compare regenerative practices with business-as-usual farming. Until this is resolved, the potential to build the scientific evidence base for regenerative agriculture will be limited.

1.2 Regenerative agriculture standards/certification (pros and cons)

There is currently no legal definition of regenerative agriculture and no restrictions on the use of the term by the UK government. This contrasts with organic foods which must meet organic production standards to be marketed as organic[4]. There has been limited analysis of the issues around regenerative agriculture certification in the peer-reviewed literature. A Web of Science search in May 2024 identified only 5 papers[5] discussing the issues surrounding regenerative agriculture certification systems (the search term included "regulation" which resulted in many papers discussing regulation of climate or water processes in regenerative agriculture which were excluded).

There have not been any studies in the UK that explicitly look into the industry attitudes towards a certification scheme for regenerative agriculture, but an Australian study provides some useful insights drawing on experiences from the organic sector (Elrick et al. 2022). The authors interviewed a range of key informants in Australia on the future for a regen ag certification label. Despite offering many criticisms of the organic certification system, the informants still felt strongly that regulation of the term "regenerative agriculture" was needed to avoid "false marketing". They advocated a centralised RA regulatory body while cautioning against too much bureaucracy or expense for farmers. A recurrent theme in the interviews was that regenerative agriculture is an inclusive movement and that any certification scheme should be built around principles of support, education and collaboration. Participatory Guarantee Schemes (PGS) were proposed as an alternative to third-party certification. These schemes have been trialled in the organic sector and include the exchange of advice and knowledge as a key element of inspections (Kaufmann et al. 2023). This approach

---

[4] Including organically grown, organically produced, grown or produced using organic principles or grown or produced using organic methods

[5] Elrick et al. (2022), Newton et al. (2020), Lemke et al. (2024),Marks (2020), Mooney et al. (2024)

would be in line with the general sentiment expressed by the informants that "a future RA certification model should put a focus on principles that support and help the producer to transition along a continuum of RA farming approaches and practices, rather than imposing dichotomous rules" (Elrick et al. 2022).

Lemke et al. (2024) also viewed the issues around certification of regenerative agriculture through the lens of experiences of certification in the organic sector. In their small survey of organic farmers, the need for an outcome-based certification scheme in regenerative agriculture (versus the process-based schemes used in organic farming) was suggested. To be viable the scheme would need to be flexible, with a list of practices specific to local conditions, a clear list of certification requirements, a third-party verification system, and tied to a premium. This was reflected in interviews with farmers in the United Kingdom, Ireland and France, who expressed concerns about future dilution of the meaning of terms like regenerative, in the absence of clear standards (Mooney et al. 2024).

Within the organic sector there is an interest in developing a set of practices that go beyond organic; these have been demonstrated in the Regenerative Organic Certified® scheme led by the Regenerative Organic Alliance[6]. The scheme uses the USDA organic production standards as a baseline and then builds in additional standards relating to soil health, animal welfare and social justice. The objectives of regenerative agriculture espoused by the scheme are outcomes-based, but the standards are principally process-based (Newton et al. 2020).

The Savory Institute is developing an outcome-based certification programme[7] which is part of the Land to Market initiative that links regenerative farmers to brands seeking to improve their environmental credentials through Corporate Social Responsibility (CSR) investments. This Ecological Outcome Verified™ programme baselines environmental indicators (e.g. soil health, biodiversity) on regenerative farms and collects more detailed data every five years to monitor status of the metrics; if improvement is not detected, farmers may lose their certification (Newton et al. 2020). In the UK, Regenerate Outcomes[8] is running a similar program with links to the Savory Institute and Gabe Brown's Understanding Ag[9]. This programme includes free

---

6 https://regenorganic.org/

7 https://savory-institute.gitbook.io/eov-manual-public

8 https://www.regenerateoutcomes.co.uk/

9 https://understandingag.com/

mentoring and training for members which reflects the ethos of the Participatory Guarantee Schemes referred to above.

Newton et al. (2020) explain that outcome-based programs may be more expensive to administer due to the additional costs associated with monitoring and advice.

The debate about certification schemes is not really a research question. The pros and cons of different types of schemes are outlined above. It is more important that the industry decides if they want to continue to allow use of the term "regenerative" in marketing with no restrictions, or if they would like to move towards an "organic" system where the term is regulated and certain criteria need to be met for it to be used in marketing.

Challenge 2: Advice and Guidance or "How to…"

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.

2.1 Growing root crops in regen systems

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[10]: "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

[10] includes article topic, title, abstract and author keywords

"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[11] (Table 17).

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.

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[12] (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[13] (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.

---

[11] "in the UK" implies authors with UK country addresses; it does not necessarily mean studies were done in the UK

[12] Stubble tillage is a term used in Europe to refer to a light harrowing prior to ploughing to control weeds.

[13] https://potato-lite.farm/

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.

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) shown in Table 18. 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[14]. 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 6.1).

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 2). 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

[14] 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.

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.

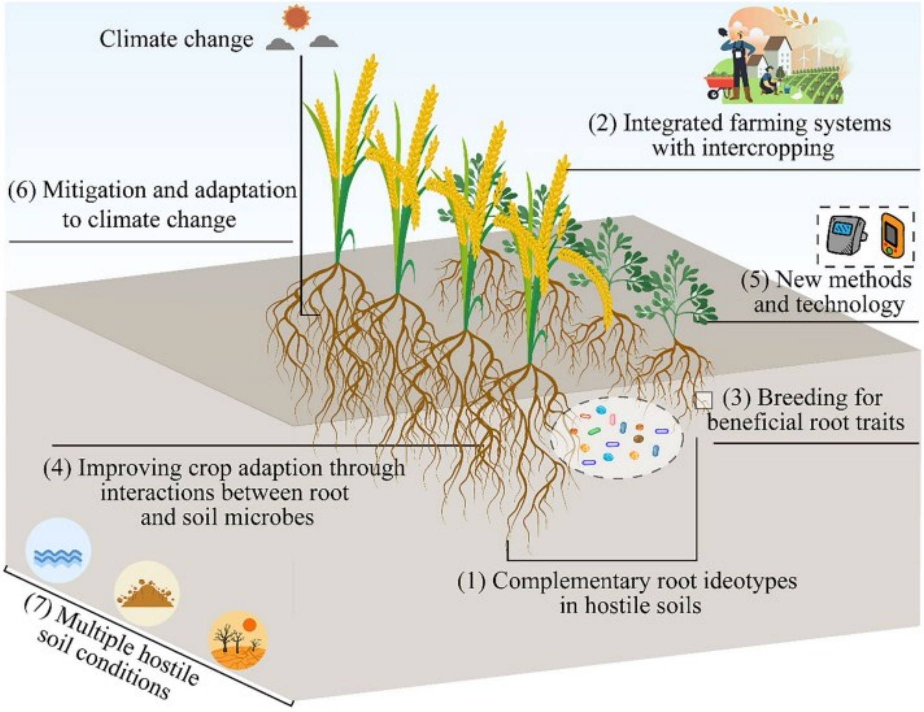
The potential of intercrops to future-proof cropping systems against climate change (6), is alluded to e.g. against waterlogging which may happen more frequently in the future. This seems particularly relevant this year when unprecedented rainfall has led to crop failures in the UK. Intercrops may provide 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.

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.

Figure 2 Image from Zhang et al (2024) illustrating seven areas for future research activities relating to roots and intercropping systems.



Several past projects have produced useful, practical information on intercropping in the UK. This includes the Nuffield Scholarship report written by Andrew Howard[15] which identified a need for breeding varieties adapted to intercropping 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[16] 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 2) 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.

[15] Available here: https://agricology.co.uk/resource/potential-companion-cropping-and-intercropping-uk-arable-farms/

[16] https://www.innovativefarmers.org/field-labs/intercropping-in-arable-farming/

Table 2 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

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

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[17] 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).

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,

---

[17] In academic literature insect pests which consume crops are sometimes referred to as herbivores

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[18]. 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.

[18] 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]).

Agrovista's Project Lamport[19] explores the use of a Berseem clover/vetch mixture that is designed to be killed by winter frost, grown with oilseed rape to reduce pest damage, improve soil health and enhance winter nutrient capture. They report reductions in slug activity and flea beetle damage and commensurate reductions in pesticide applications (in France, 60% of farmers that grow companion plants in rape are able to eliminate at least one spray for flea beetle) and a yield benefit of ~0.4 t ha^{-1} where companion plants are used.

One drawback to companion planting that has been highlighted is the potential role of the companion crop as a "green bridge" that becomes a host for pests and diseases over the winter months (Woolford and Jarvis 2017). Multi-species mixes of companions are encouraged to reduce this risk.

The Innovative Farmers intercropping project mentioned above, also explored companion planting (Bickler and Bliss 2016). An intercrop of oats with linseed was tested as a control for flax flea beetle (FFB) as well as an intercrop of oats in a crop of "peola" (peas and oilseed rape) for CSFB control. While no differences in pest pressure were detected in the linseed crop, yields of linseed were higher where oats were present; results from the peola trial were inconclusive.

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 (Li et al. 2023)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). 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

[19] https://www.agrovista.co.uk/project-lamport-2020

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.

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).

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. 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

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.

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"[20], a database on subsidiary crops[21] and a decision support tool to help filter the database to find the best crop for the user's situation[22]; all of these valuable resources could be updated and adapted for use in the UK.

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[23].

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

---

[20] AgroDiversity Toolbox (uni-kassel.de)

[21] OSCAR Cover Crop Database (uni-kassel.de)

[22] vm193-134.its.uni-kassel.de/toolbox/DST.php?language=English

[23] www.agricology.co.uk

several projects in recent years related to cover cropping (see Table 5 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[24] 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[25] (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. 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 (Table 19).

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

[24] https://www.covercropsguide.co.uk/

[25] Resources - Cover Crops (covercropsguide.co.uk)

(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[26], a solarisation method that involved a clear polyethylene sheeting covering the plot for 28 days, and flame weeding over the entire plot area[27]. 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 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 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

---

[26] 45% cinnamon (Cinnamomum verum L.) oil (cinnamaldehyde, eugenol, eugenol acetate)/45% clove oil (eugenol, acetyl eugenol, caryophyllene)

[27] broadcast flame emitting 1100^{o}C applied at 1.2 k/h (flame),

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[28] 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 3); outcomes of these should be monitored.

Table 3 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.

2.6 Regional adaptation of cover crops; particularly for cool, wet, temperate 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,

[28] https://innovativefarmers.org/field-labs/alternative-methods-for-terminating-cover-crops/

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 (see Table 19). 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 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[29] 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[30]). 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 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

---

[29] 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

[30] https://www.bostonseeds.com/products/forage-crops/brown-mustard/

(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 (see Table 20).

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[31] 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

[31] https://www.oper-8.eu/about/

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

The new Large-scale rotation experiment at Rothamsted[32] (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 4) that should be reviewed to inform future research activities around strategies to reduce reliance on herbicides in regenerative farming systems.

---

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

Table 4 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

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 section 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[33]. This usually refers to the reintroduction of ruminants into arable systems through the

[33] 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).

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[34]. 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 Section 6.2.

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[35] 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.

---

[34] https://www.organicresearchcentre.com/our-research/research-project-library/feedthesoil/

[35] 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.

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[36]. 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 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*

[36] 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)

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"[37] 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[38] 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.

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[39].

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 some of these specifically refer to regenerative agriculture (39 papers see Table 20). 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, covered

---

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

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

39 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

the benefits in their report to Defra "Evaluating Agroecological Practices". They focused their discussion on the inclusion of break crops in arable rotations[40] and reported benefits including: increased soil organic carbon, microbial diversity and diversity in general, yield[41], 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 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 4.1 Better indicators of soil biological function).

---

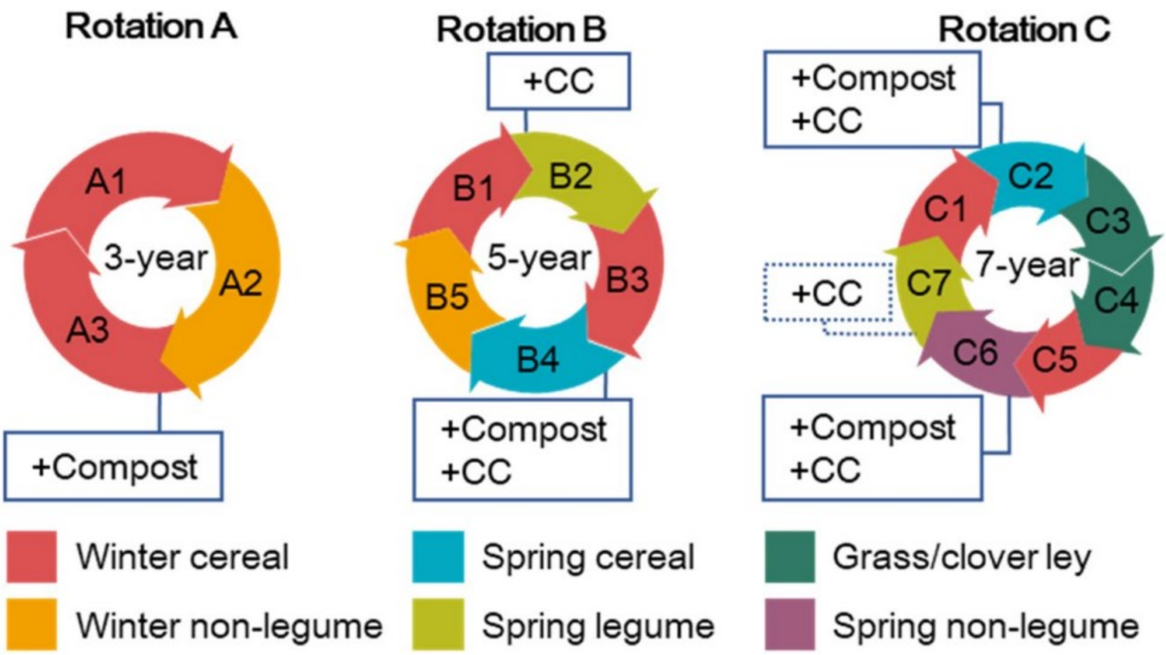
[40] Crops grown to break disease cycles in main crops, e.g. oilseed rape is a common break crop in cereal rotations. Peas and beans also serve this function.

[41] At the level of the individual crop; yields across rotations expressed in a standard unit, e.g. calories ha^{-1} are less commonly reported.

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 Section 5. The new Large-Scale Rotation Experiment (LSRE; Li et al 2023; Figure 3) 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 3 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[42] have covered crop rotations including innovations like intercropping and living mulches. In addition, the Defra projects listed in Table 5 all have some relevance to the design of crop rotations and should be taken into consideration when planning future research on rotations. 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.

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

[42] 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

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 5 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[43] 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

[43] https://www.nofence.no/en-gb/

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.

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.

Challenge 3: Crop genetics

A recurrent topic within the regenerative agriculture community is the need for crop varieties developed specifically for regenerative systems. There is a perception that the varieties identified using the Recommended List trials with minimal weed competition, high nutrient inputs and conventional tillage may not be suited to regenerative farming systems. Some of the traits considered important for regenerative systems are listed below as challenges. The evidence and knowledge gaps relating to plant materials with more genetic diversity is also discussed.

3.1 Breeding and evaluation for disease and insect tolerance

Good disease and insect tolerance is one of the main traits that varieties have been selected for in conventional breeding programmes. Using a search term that encompassed the main arable crops grown in the UK (arable OR cereal OR rapeseed OR canola OR wheat OR barley OR oats OR beans OR maize) combined with a term for insect or disease tolerance ("disease" OR "pest" OR "pathogen" OR "insect" OR "fungus" OR "virus") and a term relating to breeding/genetics (breeding OR genetics OR gene) resulted in nearly 24,000 peer-reviewed articles being identified in a recent WoS search (Table 21). Nineteen projects relating to this topic were identified in a search of past Defra projects (Table 6). These projects have built the knowledge base to develop crop breeding programmes on disease and insect resistance in cereals in the UK. The current Delivering Sustainable Wheat[44] (part of the Designing Future Wheat BBSRC Strategic Programme) work package 2 has a focus on delivering resilience to biotic stress i.e. wheat diseases such as stem rust, wheat blast, Fusarium Head Blight, Septoria Leaf Blotch, take-all root disease, and yellow rust. This rapid assessment of past research suggests that there is already a large body of knowledge on traits and genes linked with increased disease and pest resistance in major UK crops. But it is important to note that the primary focus of most research efforts in the past has been on cereals (about half of the peer-reviewed papers mentioned above focus on wheat). There is a possible gap/opportunity to put more resources into similar breeding efforts for less commonly grown arable crops that may become more prevalent as farmers move to more diversified cropping systems, e.g. beans, linseed, peas[45]. The potential to develop markets for “minor cereals” and research into their suitability for UK conditions, including susceptibility to pests and disease, was explored in the HealthyMinorCereals[46] EU project which focused on spelt, rye, oat, einkorn and emmer. These minor cereals are more commonly grown in organic and regenerative systems and may benefit from more targeted resources towards breeding for insect and disease tolerance. The current EU project: LiveSeeding[47]

---

[44] https://designingfuturewheat.org.uk/about/

[45] Recognising that the PGRO already puts considerable effort into breeding and agronomy for reduced disease and pest pressure in pulses.

[46] https://healthyminorcereals.eu/en/about-project/about

[47] https://liveseeding.eu/

works through networks of living labs across Europe (including the UK) to test modern varieties (of beans, wheat and oats in the UK) under organic production systems; this will provide useful information on the varieties which perform best with no added pesticides or fertilisers and in particular help to answer the question "does the current Recommended List (RL) system identify varieties most suited to organic and regenerative systems?". Redirection of resources towards breeding for insect and disease tolerance in a diverse range of "minor" crops should help to strengthen and build more resilience into the sector, as well as support the transition towards lower inputs of insecticides and fungicides.

Finally, in spring of 2024 the AHDB commissioned a scoping review on the impact of fungicide programmes on the performance of cereals and oilseeds varieties. This is part of the five-year RL review process which surveyed levy-payers for input. An outcome of survey was a desire for more information on varieties suited to low-input conditions. The scoping review will gather information from academic and non-academic ('grey') literature, include data provided by breeders, and examine the strength of the evidence. The key aim will be to better understand if the rankings of varieties change when grown under low-input (in this case reduced levels of fungicides) conditions. It will also provide recommendations on how to deliver improved information to farmers and identify evidence gaps. Once this report is available, it should be taken into consideration when planning next steps with breeding for disease tolerance for the crops included in the RL.

Breeding and evaluation for disease and insect tolerance was rated as a normal priority area for future research efforts. This has been a focus of past breeding efforts in the UK, particularly in cereals and oilseeds, which has been related to the size of the markets for these crops. Given the great crop diversity within regenerative systems, new initiatives should target under-represented crops such as "minor" cereals like rye, oats, spelt, as well as pulses.

Table 6 Summary of past Defra projects relating to breeding for disease and insect tolerance in main UK arable crops

Title	Year completed
Development & selection of oat germplasm and genetic stocks leading to varieties for milling, feed and new markets - AR0705	2004
Novel variation in oats to improve sustainable production, disease resistance and use - AR0706	2004
Biology and genetics of durable resistance to biotrophic pathogens of cereals - AR0712	2007
Durable cereal disease resistance: the physiological, biochemical and genetic basis. - CE0154	2003
Exploitation of sustainable disease resistance : genetics of powdery mildew and Septoria tritici - CE0155	2003
Exploiting sustainable disease resistance: facultative pathogens of cereals - CE0156	2003
Exploitation of sustainable disease resistance : yellow rust of wheat - CE0157	2003
Breeding for improved resistance to Septoria tritici - LK0913	2004
Controlling soil-borne wheat mosaic virus in the UK by developing resistant wheat cultivars - LK0930	2006
Reduced fusarium ear blight and mycotoxins through improved resistance (REFAM) - LK0932	2007
Improved Resistance to Septoria in Superior Varieties (IMPRESSIV) - LK0945	2010
The incorporation of important traits underlying sustainable development of the oat crop through combining conventional phenotypic selection with molecular marker technologies - LK0954	2009
Exploitation of resistance mechanisms associated with the introduction of new sources of mildew resistance in cereals	1994
Variation and population dynamics of cereal mildew and strategies for their control - CE0107	1994
Sustainable disease resistance: rusts of wheat. - CE0133	1999
Sustainable disease resistance: mildew and leaf blotch. - CE0134	1998
Sustainable disease resistance: facultative pathogens of ear and stem base. - CE0135	1998
Identification and exploitation of new sources of disease and pest resistance in oats - CE0144	2000
The physiological, biochemical and genetic basis of durable resistance to graminaceous diseases - CE0120	1998

3.2 Variety evaluation and breeding for root traits

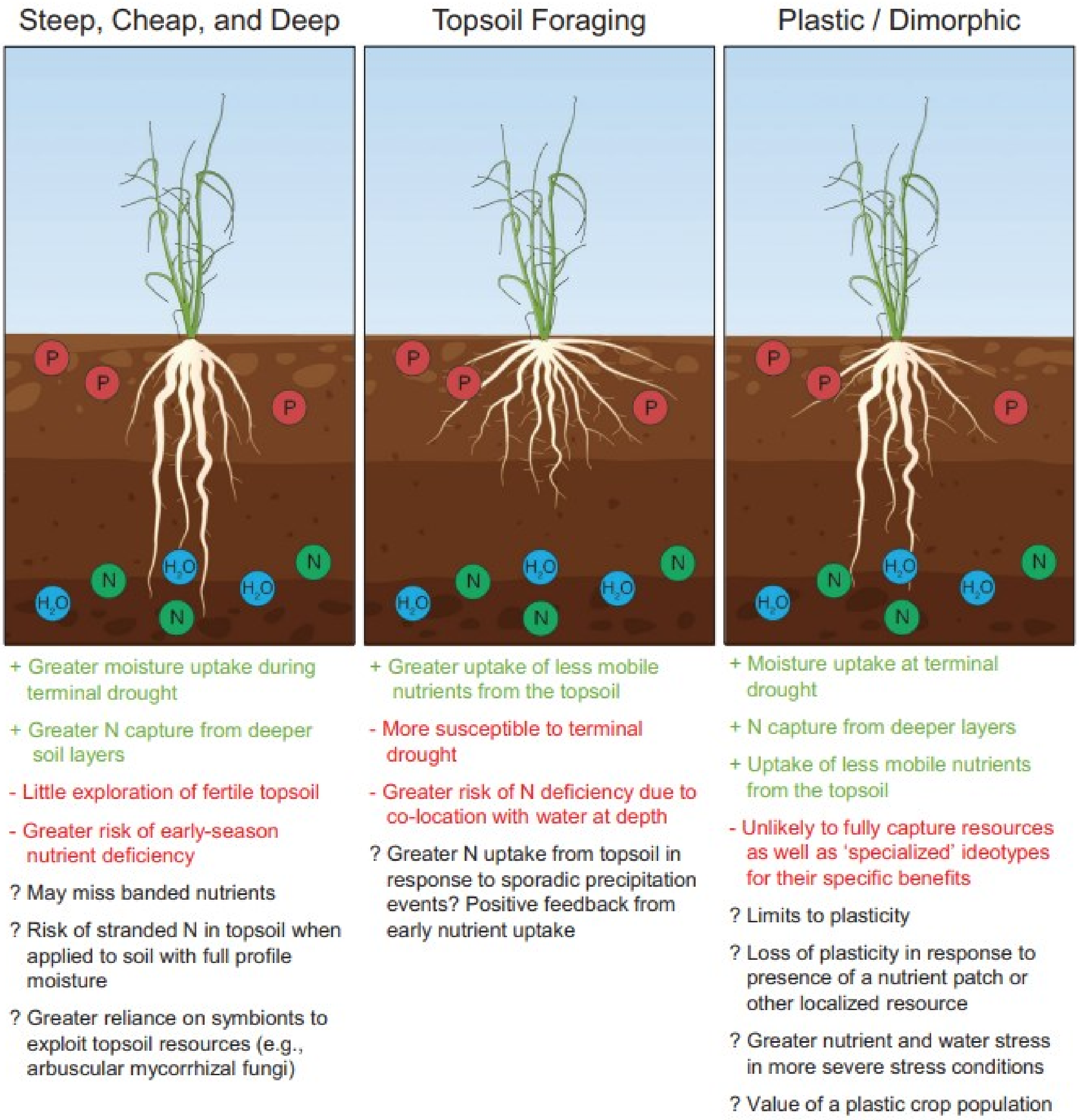
Identifying varieties with desirable root traits at no cost to crop productivity (yields) is a "holy grail" of plant breeding efforts. Reynolds et al. (2021) highlight roots as one area of research that has been underrepresented in academic literature and which could boost productivity in a range of crops and environments. This has been a particular emphasis for researchers seeking to develop varieties that will be more water and nitrogen use efficient in the face of future climate scenarios and resource limitations (Ober et al. 2021). Van Der Bom et al. (2020) review different root ideotypes and provide a useful assessment of the pros and cons of selecting for specific targets (Figure 4).

Nearly 400 peer-reviewed papers with a focus on breeding for root traits in the UK were identified in a Web of Science search and 40 of these included reference to root “architecture”. Several authors have explored the impact of modern breeding targets like semi-dwarfing genes (Kavamura et al. 2020) and reductions in below-ground competition within the crop (Fradgley et al. 2020), speculating that this may have negatively affected desirable root traits. The ideotype for roots that are efficient at water and nitrogen acquisition has been described as “steep, cheap and deep” (Lynch 2013) i.e. designed for rapid exploitation of deep soil layers. In contrast, roots systems optimised for P uptake need to have more roots in the surface layers of the soil. Considerable genetic variation in root traits has been identified in landrace (Kareem et al. 2022) and progenitor species (Leigh et al. 2022) of wheat, has been identified. This suggests that breeding programmes can target root with different architectures for improved nutrient uptake.

Apart from root architecture, selection for varieties with roots that form mutualistic[48] relationships with soil microorganisms could be an avenue for breeding crops for organic and regenerative systems. Beneficial soil organisms like free-living N-fixing bacteria, phosphate solubilising bacteria, and arbuscular mycorrhizal fungi live in close proximity (or within) crop roots and can improve the plant’s access to soil resources. Kinnunen-Grubb et al. (2020) demonstrated that modern breeding has dramatically changed the root-associated microbiome of wheat and that there is genetic variation among modern wheat, landraces and their ancestral populations. Thirkell et al. (2022) identified considerable variation in the potential for root colonisation and crop growth impacts of mycorrhizal inoculation in 99 lines of a mapping population of wheat grown in a pot trial, suggesting that there is potential to select for root-microbiome traits.

[48] A mutualistic relationship is a type of symbiotic relationship that is beneficial to both species involved.

Figure 4 Examples of (pre-defined) root ideotypes and potential trade-offs arising in environments with spatially disjunct soil resources. The positives (+), negatives (–), and uncertainties (?) of the different phenotypes on resource capture are indicated (Van der Bom et al 2020)



A Defra study (Scoping study: A framework to optimise cereal root systems. - AR0902) developed a quantitative model of wheat root systems that can be used to identify possible target characteristics for manipulating root systems (King et al. 2003). This was followed by AR0714 (A study of the scope for the application of crop genomics and breeding to increase nitrogen economy within cereal and rapeseed-based food chains) and LI0986 (Improving water use efficiency and drought tolerance in UK winter wheats) both of which included studies of genetic variation in rooting traits and their impacts on resource use efficiency. Barraclough et al. (2010) further elucidates the potential to breed for improved nitrogen use efficiency in wheat specifically, based on genotypic variation in density, architecture and physiology of roots. This work was part of the Wheat Genetic Improvement Network (WGIN)[49] (now superseded by Delivering Sustainable Wheat) a project run by Rothamsted Research that provided wheat genetic stocks, mapping populations, molecular markers and marker technologies, trait identification and evaluation, genomics, novel sequence information and bioinformatics.

All of the evidence listed above indicates that considerable resources have already been applied to understand the genetic controls on root traits that would be relevant to development of wheat varieties adapted to regenerative systems. However, as discussed in section 3.1, the focus has been overwhelmingly on wheat; there are still many gaps in knowledge about how much genetic variation and breeding potential there is to select for desirable root traits in many other important arable crops in the UK. A final key point to emphasise is that it remains extremely difficult to study root development under field conditions. This makes phenotyping of mapping populations for root traits challenging. A further research gap is in developing effective ways to study root growth in field soils.

Rooting traits have become a focus for breeders seeking to identify varieties suitable for low-input conditions and drought resistance. Significant resources have been dedicated to understanding the genetic controls on root traits in wheat varieties adapted to regenerative systems. However, there are still many gaps in knowledge regarding the extent of genetic variation and breeding potential to select for desirable root traits in many other important arable crops in the UK. This topic was scored by workshop participants as high/normal in importance. It should be noted that performance under reduced inputs (3.3) and in reduced tillage intensity systems (3.5) were identified as high priorities, and programmes addressing those targets would include consideration of root traits.

3.3 Variety evaluation and breeding for low N (and PPP) inputs

One of the key factors driving interest in root morphology and physiology is the need to develop crop varieties that will remain productive at low levels of nitrogen; these varieties will need to be more efficient than current varieties in their uptake and utilisation of soil available N i.e. they will need to have a high nitrogen use efficiency (NUE). This need is being driven by a recognition that the resources to produce

---

[49] https://www.rothamsted.ac.uk/project/wheat-genetic-improvement-network

synthetic N are non-renewable and that the manufacture of N fertiliser has a large environmental footprint. In addition, a large proportion of added N fertiliser is lost to the environment, further exacerbating the negative effects of N fertiliser. Crop varieties that can efficiently access N from inaccessible soil reserves (e.g. organic forms of N, inorganic N deeper in the soil profile) and utilise it efficiently, may help to reduce the demand for fertiliser N in the future. Sylvester-Bradley and Kindred (2009) provided a review of nitrogen use efficiency in cereals in the UK and reported a range of N capture rates from 0.77 kg N uptake for every kg N available in the soil[50] for triticale to 0.60 kg N uptake per kg available N for spring barley. The available N not taken up by the crop is at a high risk of leaching to groundwater or being converted to gaseous nitrogen (N_2 or the greenhouse gas N_2O).

Breeding strategies to improve nitrogen use efficiency include those outlined for improvements in root system architecture and microbiome associations (see Section 3.2). In addition, traits that affect NUE, partitioning, and trade-offs between yield and quality aspects need to be considered (Hawkesford and Riche 2020). A review of peer-reviewed literature identified over 1,000 peer-reviewed articles about breeding for nitrogen use efficiency in arable crops. Fourteen of those were review articles published in the UK focusing on cereals. It is clear that within the UK there is a strong body of expertise on crop breeding for improved nutrient use efficiency in cereals. These researchers based at Rothamsted Research, Nottingham University, Cambridge University, John Innes Centre etc. continue to study the genetic basis for NUE within projects like Delivering Sustainable Wheat[51].

Past projects that have addressed NUE in UK crops are listed in Table 7. Trials in the Wheat Genetic Improvement Network (WGIN) explored the interaction between crop genetics, environment and management (GxExM) comparing four wheat varieties developed during different periods[52]. The general ranking of varieties for grain N utilisation efficiency was the same at each rate of N fertiliser; suggesting that the best varieties for low N input conditions are the same as the best suited varieties for higher N rates (Hawkesford and Riche 2020). The NUE-CROP project also worked with breeders and universities to explore GxExM interactions and identify optimum systems for local contexts. The G part of this equation involved identifying traits linked to NUE and the molecular markers of those traits to speed up breeding. The final project report includes this statement about wheat:

---

[50] This included soil N supply and fertilizer N

[51] https://designingfuturewheat.org.uk/about/

[52] Maris Widgeon was introduced in 1964, Avalon 1980, Hereward 1991 and Solstice 2002

Partners found little interaction with fertiliser level suggesting that that there is little prospect in the European adapted winter wheat gene pool for successfully breeding new genotypes that can produce more yield specifically at low fertilizer levels. The exception was for organically bred varieties, which in some cases out-yielded conventionally bred varieties under organic conditions.

This outcome reflects the outcomes of the WGIN work reported above. The exception for crops grown under organic conditions suggests that genotypes developed for organic systems have traits not related to N supply (e.g. better competition with weeds due to taller growth habits) that allow them to perform well in these systems.

Table 7 Summary of past projects in the UK linked to crop breeding for nitrogen use efficiency

Funder	Title	Year completed
Defra	Development & selection of oat germplasm and genetic stocks leading to varieties for milling, feed and new markets - AR0705	2004
Defra	A study of the scope for the application of crop genomics and breeding to increase nitrogen economy within cereal and rapeseed based food chains. - AR0714	2005
Defra	Lupins in Sustainable Agriculture - LISA - LK0950	2009
Defra	Genetic Reduction of Energy use and Emissions of Nitrogen in cereal production, GREEN grain - LK0959	2009
Horizon 2020	Solutions for improving Agroecosystem and Crop Efficiency for water and nutrient use (SolACE)	2022
EUFP7	Improving nutrient efficiency in major European food, feed and biofuel crops to reduce the negative environmental impact of crop production (NUE-CROPS)	2014
BBSRC/ Defra	Wheat Genetic Improvement Network (WGIN) - BB/P016855/1 and CH1090	

Other European projects relevant to this challenge with activities in the UK include HealthyMinorCereals[53] and SolACE[54]. In both of these projects different varieties of the crops included (in the case of SolACE: potatoes, maize, wheat) were assessed

53 https://healthyminorcereals.eu/en/about-project/about

54 https://www.solace-eu.net/about.html

under varying levels of nutrient input, providing additional evidence on the GxM component of the GxExM interaction.

The 2022 review of the AHDB Recommended List (RL) project identified a need for varietal performance information under lower-input scenarios, including crop nutrition. A scoping review[55] has been commissioned that will compile and assess the evidence for varietal differences in nitrogen use efficiency (NUE) or the rank order of varieties for yield at lower nitrogen rates. This information will be used to guide AHDB in design of future RL trials and in how to deliver information on varietal performance under low N rates. This review is scheduled to be completed in May 2024 and its results should be taken into consideration when designing next steps in addressing this regenerative agriculture challenge.

Crop varieties capable of efficiently accessing nitrogen from inaccessible soil reserves, such as organic forms of nitrogen and inorganic nitrogen deeper in the soil profile, and utilizing it effectively, can potentially reduce the demand for fertilizer nitrogen in the future. N uptake efficiency traits are predominantly associated with rooting abilities (as mentioned above). Additionally, there are a range of crop traits influencing nitrogen utilization efficiency, partitioning, and trade-offs between yield and quality that must be considered. A range of crop traits also affect a crop's ability to maintain performance under a disease or pest challenge, performance under untreated conditions is part of the AHDB Recommended List evaluation. However, farmers would like to be able to access information on performance under low-input conditions more easily to support variety choices. This was identified as the highest priority area for variety evaluation.

3.4 Variety evaluation and breeding for weed competitiveness

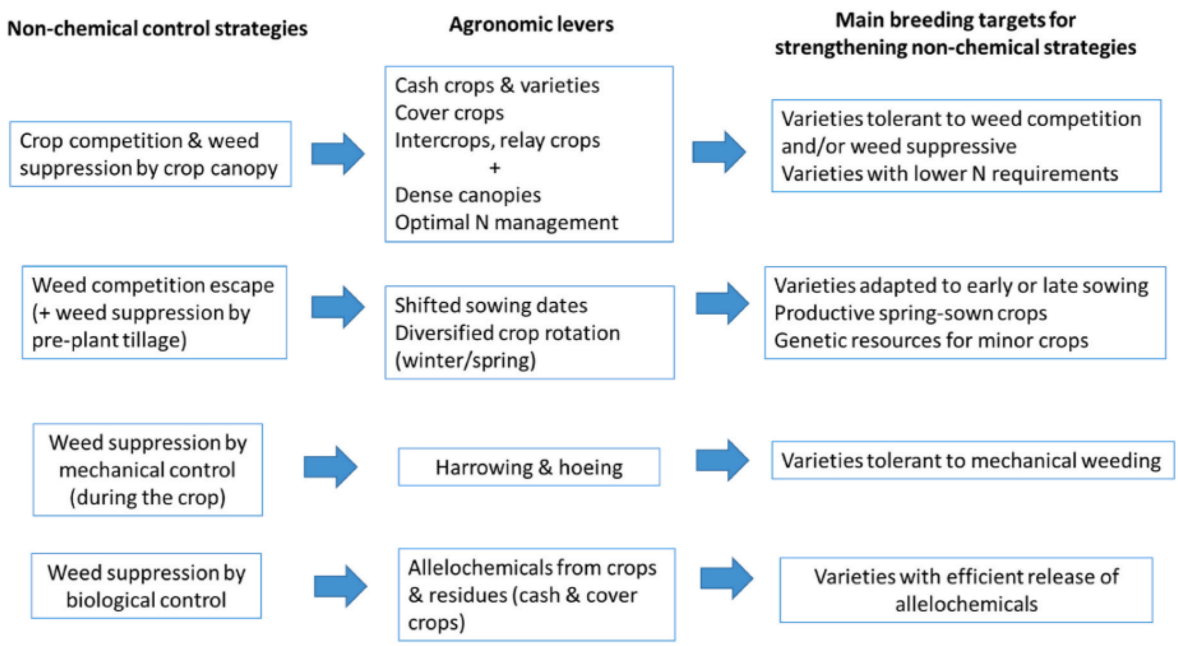
Alongside traits that improve resistance to disease and insects and improve nitrogen use efficiency, varieties grown in regenerative systems should be able to compete against non-crop plants (interspecies competition) effectively to reduce reliance on herbicides. Traits that are beneficial for weed competition will also be useful for crops grown with companion crops (see Section 2.3) and living mulches (see Section 2.4). The reliance on herbicides in conventional farming systems has meant that very little breeding effort has been invested in traits that might improve interspecies competitiveness. A Web of Science search that included terms for arable crops and breeding as well as "weed competition" OR "weed suppression" OR "allelopathy"

---

[55] Impact of nutrient scenarios on the performance of cereals and oilseeds varieties (scoping review) | AHDB

resulted in 189 papers being identified. A quick review of these papers identified several useful reviews. Debaeke et al. (2024)provide an up-to-date summary of the crop functions and traits that can be improved through breeding to enhance non-chemical weed management. They explain that crop competitiveness against weeds may be a result of a high degree of weed suppression by the crop or a high tolerance to weed competition. Traits of crops that can compete successfully against weeds include early vigour, canopy closure or light interception. Canopy closure is a function of leaf area, leaf habit, plant height, growth habit, growth rate and tillering capacity for cereals. Root system architecture and functioning may also affect competitive ability through access to below-ground resources. Figure 5 summarises the main breeding targets for strengthening non-chemical strategies.

Figure 5 Non-chemical weed control strategies, agronomic levers and main breeding targets. From Debaeke et al. 2024



Allelopathy (see Section 2.7) is a mechanism commonly studied in weed suppressive crops. Benzoxazinoids (BX) have previously been identified as the most potent allelochemicals produced by species including wheat, triticale and rye (Reiss et al. 2018; Hussain et al. 2022). Rye, in particular, is known for its weed-suppressing characteristics; genetic variation in this trait suggests that there is potential to selectively breed rye varieties for high weed suppression (Rebong et al. 2024), which would be an important target for cover crop breeding programmes. Various other authors discuss the potential to selectively breed crop varieties for allelopathy and competitive ability against weeds (e.g. Worthington and Reberg-Horton 2013). It is notable that most of the literature on allelopathy seems to have been published ten to fifteen years ago, with little recent activity in this area.

Compared to breeding for disease and insect tolerance, weed competitiveness has not received much attention from Defra. There is one project listed on their database: CE0616 Weed competition and crop canopy manipulation in winter wheat (2001) which appears to be related to wheat breeding for weed suppression, however, it was not possible to locate the report from this project. The LiveSeeding[56] project, which is running until 2026, includes on-farm trials with organic farmers in which weed populations in a selection of commercial wheat and bean varieties are monitored. This should provide useful baseline information on the genetic variation among some commercial varieties for weed suppression.

Clearly, there has been a deficiency in efforts to selectively breed our major arable crops for traits linked to weed competitiveness; this is an area of research that should be developed to support the transition to less herbicide-reliant, regenerative systems of crop production.

Competitiveness against non-crop plants, including weeds and living mulches, is crucial in regenerative agriculture crops. Speed of emergence and leaf architecture are considered to be key traits in determining competitiveness. However, since herbicides are commonly used in variety development and Recommended List trials, conventional crops have not been assessed in conditions where weed competitiveness is favoured. This presents a significant gap in research and was identified at the stakeholder workshop as an area that should be developed to support the transition to less herbicide-reliant, regenerative crop production systems.

3.5 Variety evaluation and breeding for performance in reduced tillage systems

The use of reduced intensity of tillage in regenerative agriculture systems, represented by the search terms no-till, conservation till, zero till, direct seeding, direct drill, strip-till, minimum till/min till, reduced till or reduced intensity till in our Web of Science searches, is a key principle of regen ag. As discussed above for other management practices and growing conditions, there is an interest in understanding whether the

[56] https://www.organicresearchcentre.com/our-research/research-project-library/liveseeding/

ranking of varieties in the RL trials which are conducted using conventional tillage practices, would be the same under reduced tillage intensity[57].

The recent RL review[58] identified establishment technique[59] as one of the topics selected by respondents for "further improvement", so there is certainly a perception in the industry that the current RL trials do not identify the best varieties for reduced tillage systems. Reduced tillage intensity methods can result in changes in soil properties and resulting crop root morphologies (Qin et al. 2018); this may include higher soil bulk densities which cause slower root growth and increased root diameters, sometimes with more root branching. Systems with no ploughing in the spring, can result in cooler and wetter soils which may slow down seed germination and seedling growth, as well as affecting mineralisation of nutrients from organic reserves in the soil (Alletto et al. 2011). Soils that are not regularly ploughed develop more distinct stratification or layers; this can particularly affect immobile nutrients like P which can be concentrated in the topsoil and depleted in deeper soil layers (Qin et al. 2018). All of these factors will result in a set of soil conditions that are quite different from those under which RL trials are currently conducted.

A search for peer-reviewed papers globally that considered breeding for reduced tillage intensity in arable crops resulted in 397 papers being identified. These were filtered for review papers to identify those highlighting the key approaches and state of knowledge on this topic: these 47 papers were then screened manually and key information was extracted. Many of these papers focus on exploring the evidence that there is a Genotype x Tillage interaction affecting yields of major arable crops. Carena et al. (2009) focussed on maize but provide a useful example of the type of study that is needed to determine if breeding programmes that include tillage are necessary. They reviewed twelve studies on maize that included genotype (G) and tillage (T) as factors and found few significant GxT interactions. Their conclusion was that the lack of significant GxT interactions meant that growers could select corn hybrids for no-till systems using results from performance trials conducted under conventional tillage. Herrera et al. (2013) conducted a similar review of studies on wheat that included GxT interactions. Of the 12 studies they identified, 8 reported a significant GxT interaction with 7 of those resulting in a change in genotype ranking; they highlighted the importance of parent selection in breeding for adaptation to tillage management.

---

[57] In statistical terms, answering the question: is there a significant Genetic x Management interaction for that management practice.

[58] https://ahdb.org.uk/news/initial-results-from-the-recommended-lists-rl-review

[59] Presumably this refers to methods like direct drilling/no-till.

They also included a summary of traits that improve adaptation to no-till systems. These include traits associated with emergence of vigorous seedlings and resistance to the changed spectrum of diseases in no-till systems[60]. For example, increased amounts of straw residues on the soil surface in no-till wheat systems have been identified as increasing the risk of infection from Septoria nodorum blotch (SNB) (Downie et al. 2021) requiring ongoing programmes to maintain genetic resistance to this disease. Joshi et al. (2007) also identified traits such as faster emergence, ability to germinate when deep seeded and enhanced resistance to new pathogens and insect pests which may survive in crop residues. An additional trait identified by Joshi et al. (2007) was the decomposition rate of the crop residues: they suggested that in many cases, fast decomposition of residues is desirable to increase the release of nutrients and reduce the risk of pathogens. The optimum rate of residue decomposition in UK conditions is something worth further consideration.

There are few projects in the UK that have explored GxT interactions; however, the new NIAB project: Exploiting novel wheat genotypes for regenerative agriculture[61] should provide valuable insights into the performance of wheat under regenerative agriculture practices, including reduced tillage intensity. This work is key to determining if there is a GxT interaction for wheat varieties in the UK and will help decision-making around the direction of resources to breeding programmes for the RA community. As previously discussed, there appears to be a focus on wheat in much of this research. An obvious challenge/gap is in breeding for reduced tillage intensity in species apart from wheat that represent the diverse range of crops that may be grown in future regen ag rotations.

The recent Recommended List (RL) review identified establishment technique as one of the topics selected by respondents for "further improvement" in the RL trials. Plot drills are relatively lightweight and not well suited to replicating on-farm direct drilling approaches and more work will be needed to fully incorporate establishment methods as part of small plot trials. Few projects in the UK have explored this topic; however, the NIAB project mentioned above (Exploiting novel wheat genotypes for regenerative agriculture) will be crucial in determining if there is a need to select wheat varieties for these systems. An obvious challenge and gap lies in breeding for reduced tillage intensity in species apart from wheat.

---

[60] Refer to the paper for a detailed list of these traits.

[61] Exploiting novel wheat genotypes for regenerative agriculture | NIAB

3.6 Selection and agronomy of variety blends

Regenerative farmers are embracing the principle of enhanced genetic diversity of their seed sources as a route to improved environmental and economic resilience. This can be represented along a spectrum of diversity from a simple blend of two varieties grown within the same field through to established heterogeneous populations of crops. Wolfe and Ceccarelli (2020) provide a useful set of definitions for the various genetically diverse seed materials used in cereal production. These include variety mixtures or blends that are "static" meaning they are re-constituted from their original component varieties each growing season, and "dynamic" mixtures or blends which are planted using seeds harvested from a static mixture. If seeds from a dynamic mixture are saved and replanted over several seasons, natural segregation, recombination and selection will occur, so that the mixture becomes a "population". Populations adapt to their local environments and become more stable than mixtures over time and across locations.

There is already a good body of work globally on the ecological principles and application of varietal mixtures in cropping systems (see Table 22). These studies explore the ecological interactions that can make mixtures effective including complementarity (niche differentiation and resource partitioning), facilitation (where fitness of neighbouring plants is increased through inter-plant interactions), and compensation (when stronger individuals increase their yields to compensate for weaker individuals) (Creissen et al. 2016). Reports of effective use of varietal mixtures are included from Europe (Costanzo and Bàrberi 2016; Lazzaro et al. 2018) and North Africa (Ben M'Barek et al. 2020).

Work on cereal blends or mixtures in the UK has been led by researchers at the James Hutton Institute (formerly the Scottish Crop Institute) who worked on variety mixtures of barley since the 1990s (Swanston and Newton 2005). They have reported numerous benefits from varietal mixtures, in particular, enhanced resistance to disease with maintenance of malting quality so essential to distillers and higher yields of blends compared to components in the mixture. The Organic Research Centre in the UK conducted studies on varietal blends of wheat in the early 2000s reporting slightly higher values for key agronomic variables, e.g. leaf area index, total biomass, and yield, compared to the mean of the component varieties, although mixtures did not outyield the best of the pure varieties (Döring et al. 2015). Criessen et al. (2016) did similar work on barley at the John Innes Centre, finding yields of mixtures comparable to the best-performing monocultures with higher yield stability. They recommended varietal mixtures to stabilise productivity and increase crop genetic diversity without the need for extensive breeding efforts.

Researchers in the organic and low-input communities have continued to study variety blends. The European projects: Healthy Minor Cereals[62] and SolACE[63] both included treatments that were varietal blends in their studies of cereals in the UK. The Organic Research Centre, in collaboration with Organic Arable, has included a variety of blends in its farmer-participatory trials networks, including LiveWheat[64] (2020-21) and now through the Horizon Europe Project LiveSeeding[65]. These projects have demonstrated that two-way blends frequently outyield the mean of the two-component varieties and, in some cases, result in yields higher than the best pure variety.

The AHDB now recognises the interest among the arable community in using mixtures of varieties for better resilience to weather extremes and disease pressures. They offer a variety blend tool to support farmers who are looking to make varietal choices for combination into field blends, particularly for wheat, allowing for 3-way or 4-way combinations. However, many regenerative agriculture farmers are exploring more complex blends and considering species beyond wheat. Determining the best variety blend can be highly context-specific, necessitating applied research on-farms with networks of farmers. There remains a gap in knowledge regarding how to select the optimal varieties for creating mixtures, as well as a need to identify the 'sweet spot' where the benefits of genetic diversity are maximized while minimizing the complexity of mixture development.

The AHDB already offers a variety blend tool to support farmers who are looking to make varietal choices for combination into field blends, however, many regenerative agriculture farmers are exploring more complex blends and considering species beyond wheat. Determining the best variety blend can be highly context-specific, necessitating applied research on-farms with networks of farmers. Stakeholders scored this as a normal level of priority.

3.7 Impacts of variety blends on crop quality and markets

For variety blends to become more easily implemented in regenerative agriculture systems, it's crucial to understand their impacts on crop quality and ensure markets

---

62 https://healthyminorcereals.eu/en/about-project/about

63 https://www.solace-eu.net/index.html

64 https://www.organicresearchcentre.com/our-research/research-project-library/farm-based-organic-variety-trials-network/

65 https://www.organicresearchcentre.com/our-research/research-project-library/liveseeding/

for the harvested product. Concerns may be raised about the potential of the blend to achieve the minimal quality requirement, e.g. protein and gluten contents for bread wheat and malting quality of barley. There are also concerns about the predictability/consistency of quality for high-value markets.

However, concerns about consistency in quality were not supported by research done at the Scottish Crop Institute on malting barley mixtures (Swanston et al. 2006). They found that mixtures of barley grown at several sites were more consistent in quality than the single varieties, and that they also had reasonably high levels for key quality indicators.

Concerns about product quality of blends relate to general concerns about how differences in product quality resulting from regenerative agriculture practices might impact the wider food system (see section 5.4: The impact of regenerative agriculture on product quality and end-market use). If protein contents of blends are lower than the required levels for bread wheat, more wheat may be diverted to the feed wheat market. This could lower production costs in the livestock sector, but also potentially increase costs for industrially-produced bread. On the other hand, some businesses (e.g. WildFarmed) are requiring their producers to grown genetically diverse blends and populations of wheat, and they use the possible improved food quality of this wheat as a unique selling point for their product. Unpicking these effects requires a multidisciplinary research effort, ideally integrated into a larger research program that examines the impacts of transitioning to regenerative farming on the whole food system. Projects funded by the UKRI's Transforming UK Food Systems programme like Fix Our Food[66] and H3[67] (Healthy Soil, Food, People) are exploring the food system impacts of a transition to regenerative farming and should provide useful insights into this question.

For variety blends to become more easily implemented in regenerative agriculture systems, it's crucial to understand their impacts on crop quality and to ensure that there are markets for the harvested product. This necessitates a multidisciplinary research effort, ideally integrated into a larger research program that examines the impacts of transitioning to regenerative farming on the food system. Projects like Fix Our Food and H3 (Healthy Soil, Food, People), funded by the Transforming UK Food Systems UKRI programme, should provide valuable insights for future projects. This work could be linked with challenge 3.6.

---

[66] https://fixourfood.org/

[67] https://h3.ac.uk/

3.8 Heterogeneous plant materials[68] – how to enable their use

The Organic Research Centre has led research activities in the development of genetically diverse, heterogeneous plant materials (HM or plant populations, see box) since the early 2000s. At that time, Professor Martin Wolfe developed the "YQ" Composite Cross Population (CCP; ORC Wakelyns Population) in collaboration with the John Innes Centre as part of Defra-funded project AR0914 (2001 - 2006). A composite cross population is created by crossing a number of plants from different lines, and subsequently bulking seeds from the resulting offspring (Döring et al. 2011). YQ was developed by crossing 20 parent varieties selected for either high yields (Y) or high bread making quality (Q) and bulking the seeds from the F2 generations of all 190 crosses (Döring et al. 2015).

Current regulations limit the ability of farmers to save and trade HM since these materials do not comply with current seed marketing laws (particularly the requirement for Distinctiveness, Uniformity and Stability). The Seed Marketing (Heterogeneous Material) (Temporary Experiment) (England) Regulations 2023 have provided the opportunity for work to continue on plant populations. This work is primarily led by the UK Grain Lab[69] in collaboration with the Organic Research Centre.

In 2023, the Organic Research Centre was commissioned by Defra to conduct a research and policy review on plant populations with a focus on wheat (Bickler et al. not yet published by Defra[70]). This report should be read for an in-depth discussion about this subject area. It includes a useful summary of outstanding questions for research and development. Several of these are relevant to enabling their use. These include:

In evolutionary plant breeding, crop populations with a high level of genetic diversity are subjected to the forces of natural selection. In a cycle of sowing and re-sowing seed from the plant population year after year, those plants favored under prevailing growing conditions are expected to contribute more seed to the next generation than plants with lower fitness. Thus, evolving crop populations have the capability of adapting to the conditions under which they are grown. (Doring et al. 2011)

1. Improved traceability, monitoring and information gathering processes. There is a traceability tool being

---

[68] Search terms used for 3.8 and 3.9 were taken from the paper by Wolfe and Ceccarelli (2020) which provided clear definitions for landraces, composite cross populations, heritage varieties and heirloom varieties.

[69] https://www.ukgrainlab.com/

[70] The report is still under review by Defra.

developed by the UK Grain Lab that has the potential to incorporate further functionality for information sharing and record-keeping, for example on seed quality, agronomic performance, and baking quality. This tool could bring together different types of data to deliver an improved understanding of both the potential application of HM (e.g., field performance or baking formulas) but also to facilitate data collection that can feed into synthesising the wider values associated with the use of HM.

2. Implementation of alternative approaches for variety registration and seed certification Alternative approaches to variety registration, seed identification, description and testing need to be considered as the current regulation is limiting the potential application of HM. There is a need for improved understanding of how description of HM characteristics, breeding methods, parents, selection and management, and region and year of production can be used to provide assurance of HM quality and support seed certification. This would help to remove registration and certification as blockers to the development of new diverse plant populations of arable crops.
3. Creating suitable opportunities for farmers to sell the grain of HM The report by Bickler et al. (unpublished) highlights the need for creative thinking about ways to develop new markets for HM products. There is a need to scale up marketing models from local, niche opportunities, e.g. through artisan bakeries, to markets that can supply larger retail outlets and exert a “pull” force on the sector, creating a demand for HM products. In parallel with developing new markets, concerns over the consistency of product quality for HM crops need to be addressed. Questions about the stability of product quality over successive generations of populations need to be resolved. There is a perception that HM will have a higher level of inconsistency but testing of variation across a range of parameters in HM versus pure-line varieties will allow the extent of genetic versus environmental variation within and between environments and grain lots to be determined.

Initiatives like the UK Grain Lab, spearheaded by Steven Jacobs (OF&G), Josiah Meldrum (Hodmedods), and Edward Dickin (Harper Adams), are supporting farmers in utilising populations like Wakelyn’s YQ wheat. The Organic Research Centre continues to pursue opportunities to develop markets for HM products and to support policies and regulations that will allow HM to be developed through evolutionary plant breeding as an alternative to commercial varieties. While stakeholders ranked this as normal in terms of importance for action, this an area

where there is novel and forward-thinking farmer-led experience that is at the forefront of the shift towards more regenerative sources of seeds.

3.9 Heterogeneous plant materials – evidence of impacts on and off-farm

As already explained in Section 3.8, much of the work on HM has been conducted by the Organic Research Centre with seminal papers by Weedon et al. (2023), Phillips and Wolfe (2005), Döring et al. (2011) and Doring et al. (2015) (the unpublished report by Bickler et al. has a comprehensive list of citations available on request from ORC).

Evidence for on-farm impacts under UK conditions has mainly been restricted to studies using the YQ population described above. For example, Costanzo and Bàrberi (2016) found that YQ performed similarly to pure-line varieties across a network of organic farms in England. In a synthesis of studies (Bickler et al. unpublished) the conclusion was that genetically diverse wheat grown under organic or low-input conditions generally has yields that are comparable or superior to modern pure-line varieties for both yield and yield stability. In contrast, in conventional production systems conventionally bred varieties often outyield HM wheat.

Other complex mixtures, such as the Noroque wheat population used by WildFarmed, maximise the benefits of genetic diversity for resource acquisition and crop resilience, and are developed through farm-saving seeds. Millers Choice Population is also grown by some farmers (see: http://www.bicga.org.uk/hub.php?ID=60), and Cope Seeds markets pre-blended mixtures of wheat varieties that farmers may use to start their own population of wheat through saving seeds and replanting over several years. Some of these HM have been included in trials in the Horizon Europe LiveSeeding project, but results from these on-farm trials have not been published yet.

It should be noted that even when farmers report lower yields for populations of wheat, some farmers continue to grow them with an expectation that they will have higher protein content and quality, more disease resistance, and be better able to compete with weeds in organic systems (Bickler et al. unpublished). These are some of the additional impacts attributed to HM seeds.

The limitation of most of the research work done with HM in the UK is that the focus has been primarily on the YQ wheat population (Bickler et al. unpublished). But YQ is just one case, which was developed with a balance between yield and quality in mind that does not necessarily translate into obvious end-uses. Investment in more and different populations is required to improve understanding of what can be expected from HM in different contexts.

Using diverse, farmer-selected seeds implies developing an alternative seed system with impacts beyond the farm gate. Any projects supporting the development of these materials should include an analysis of impacts on the wider food system. The work on variety blends mentioned in Section 3.7 could also be extended to include these more diverse seeds.

Challenge 4: Soil health

4.1 Better indicators of soil biological function

Maintenance of soil health through feeding and supporting a diverse soil microbial population is the foundation of regenerative farming systems. The regenerative farming community are particularly interested and engaged with the concept of "soil biology" and in many cases have pursued additional qualifications (e.g. Dr Elaine's™ Soil Food Web courses[71], Nicole Masters' courses in soils offered through Integrity Soils[72]). These courses focus on assessing populations of fungi, bacteria and microfauna (e.g. protozoans), as well as root colonisation by arbuscular mycorrhizal fungi (AMF) using techniques in basic microscopy; some laboratories also offer these assessments, e.g. Envirolizer[73]. In parallel with growth in on-farm microbial community assessment techniques, rapid DNA-based methods for fingerprinting soil microbial communities have been developed and are offered by some laboratories (e.g. Fera Sciences "Big Soil" project[74], NatureMetrics eDNA[75]).

The AHDB conducted extensive research into indicators of soil health including biology in the Soil Biology and Health Partnership[76] (2017-2022). They highlighted the gap between the range of indicators for soil biology developed by the research community and the guidance needed to use these indicators to make management decisions on farm. They reviewed and evaluated molecular (DNA) approaches to analysing soil health providing a useful, robust analysis of the value of these techniques for on-farm decision-making (Elphinstone et al. 2018; Dussart et al. 2023). The recommendation from their work on molecular techniques was that: "With no robust UK benchmarks for biological communities (and DNA-based testing costly), the

---

71 https://www.soilfoodweb.com/about/

72 https://integritysoils.com/

73 https://envirolizer.com/soil-fertility/soil-analysis/

74 https://www.fera.co.uk/crop-health/introducing-the-big-soil-community

75 https://www.naturemetrics.com/?gad_source=1&gclid=Cj0KCQjwsPCyBhD4ARIsAPaaRf37GWSIoyJQfoJfxVcPzKiMUD158aaHb-bp78D1FvOOCmWLVE1EbQAaApGrEALw_wcB

76 Soil Biology and Soil Health Partnership | AHDB

research did not recommend using such approaches for the routine monitoring of soil health."

To create the shortlist of indicators of soil health, a selection of 13 potential biological indicators were ranked by experts using a logical sieve approach that scored each indicator based on relevance to agricultural and environmental impact and practicalities of use. The list of indicators reviewed at this stage included the DNA-based techniques mentioned above (microbial community structure and diversity) and some of the measures used by the Soil Food Web practitioners, e.g. AMF root colonisation, total fungi and bacteria, nematode communities. However, none of these were included in the final shortlist of biological indicators in AHDB's Soil Health Scorecard[77] with only microbial biomass, earthworms and respiration selected. The current version of the scorecard only lists earthworms as a biological indicator, although some commercial laboratories are offering a more complete soil health check that includes the Solvita CO_2 burst test, a measure of soil respiration that integrates the size and function of the microbial community with the availability of carbon sources in the soil. Recently the UK Centre for Ecology and Hydrology launched a web-based tool for assessment of soil health[78] that builds on the AHDB Soil Health Scorecard approach. This tool allows the user to benchmark their soils against others across the UK from similar land uses and soil types. It uses just four indicators of soil health: organic matter, earthworm counts, pH and bulk density.

A Web of Science search for indicators of soil biological health using the following search terms: ("biology" OR "microbiology" OR "ecology" OR "microbial") AND ("indicator" OR "metric" OR "test") AND ("soil quality" OR "soil health") returned 973 papers (Table 23). Considering that a fairly comprehensive review of literature was included in the AHDB report on biological indicators of soil health published in 2023 (Dussart et al. 2023) we filtered these papers to select only those published from 2022 to now (230 papers). A quick scan of these papers identified a few indicators that may not have been included in the original AHDB project, e.g. Redox potential (Mattila 2024), microbial response (Joos et al. 2023), permanganate oxidisable carbon (Christy et al. 2023), molecular gene markers (i.e. indicators of specific functions within the microbial community) (Bhaduri et al. 2022), and many more!

A common theme in discussions with regenerative farmers about soil health is the fungal:bacterial ratio of their soils. Nicole Masters described the work of David Johnson

---

77 https://ahdb.org.uk/knowledge-library/the-soil-health-scorecard

78 https://connect-apps.ceh.ac.uk/soilhealth/

from Chico State University in her popular book: For the Love of Soil (Masters 2019). Johnson advocates increasing the biomass of fungi in the soil relative to bacteria to promote more retention of carbon; the Johnson-Su composting method he developed with his wife (Hui-Chan Su) is practised by many regenerative farmers seeking to produce a fungal-rich inoculant for their soils. However, there are no peer-reviewed publications available on the Johnson-Su bioreactor or on how it can be used to alter soil fungal to bacterial ratios. Fungal:bacterial ratios have been used as indicators of effective nutrient cycling in ecosystems (see details in the recent review by Fierer et al. 2021) but fungi and bacteria occupy overlapping niches and functions in the soil and F/B can vary for many reasons, making interpretation of the ratio difficult. Only five papers were identified from the 973 listed above that explicitly mention fungal:bacterial (or bacterial:fungal) ratios. Interpretation of results of studies that report fungal:bacterial (F/B) ratios is further complicated by differences in methodologies for calculating these ratios. Specialists trained on Soil Food Web courses are using microscopy to determine sizes of each community. Peer-reviewed papers may use phospholipid fatty acid (PLFA) techniques to quantify fungal and bacterial biomasses. This approach was used by Dangi et al. (2024) who looked at effects of differences in F/B for crops grown following durum wheat; they reported a higher F/B when any crop was grown compared to bare fallow. They speculated that this might impact on carbon storage stating that "fungi contribute more C storage compared to bacteria". But this conclusion is confounded by the fact that the crops themselves contribute more carbon than a fallow system. Zhu et al. (2023) also used PLFA to determine fungal and bacterial biomasses and F/B (Figure 6). They showed that ratios were similar when either no or all of the corn stover was retained in an 8-year study of corn grown in monoculture. This demonstrates the difficulty of interpreting results of F:B; in the same study more direct measures of soil health like soil C and N and dissolved organic carbon were all

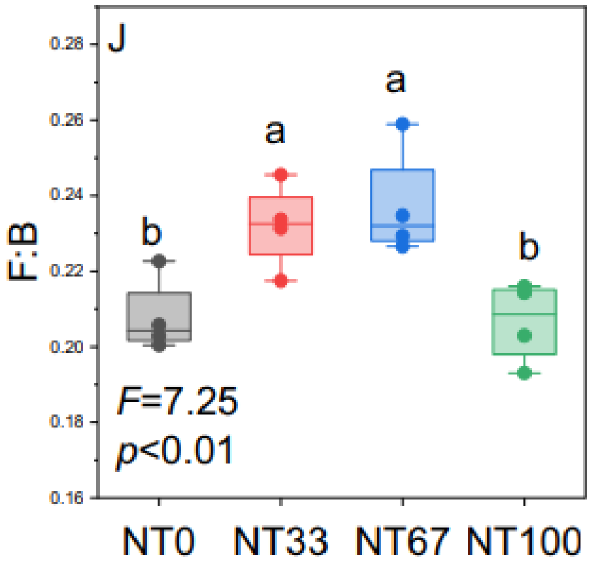


Figure 6 Extracted from Zhu et al (2023) showing fungal to bacterial ratios measured using PLFA for soils under no-till management with 0% (NT0), 33% (NT33), 67% (NT67) or 100% (NT100) of corn stover retained in the field.

significantly higher when corn residues were retained but these important differences were masked by the F:B ratio. Like many of the other biological indicators discussed above, the challenge with F/B is in relating it to soil functions and using it to make management decisions. Without the establishment of thresholds, which will likely vary with management and a variety of soil properties (e.g. carbon contents, pH, soil texture), it is not possible to reliably use measures of soil F/B to make informed decisions on management.

Defra is committed to establishing a soil health indicator under its 25 Year Environment Plan Outcome Indicator Framework[79] and will be supporting farmers to establish their own soil health baseline. Recent projects[80] funded by Defra and UKRI are exploring new approaches to measuring soil biology and function under UK conditions. The TRUTH project[81] tests PES Technologies' soil sensor which "sniffs" volatile compounds from the soil and links them to biological properties. Verdant Carbon in Kent is working with NIAB to develop an improved approach to assessing soil biological communities calibrated to UK conditions. These may result in more refined methods of assessing soil biological health. Outcomes of these projects should be reviewed before embarking on new research to develop better indicators of soil biological function.

Maintaining soil biological health and function is a fundamental principle of regenerative agriculture. Farmers are eager to learn new ways to assess soil health on their farms. Soil biological indicators were evaluated as part of the AHDB Soil Biology and Soil Health Partnership (NIAB, ADAS, Fera, SRUC); whilst research indicators are available, there are currently no approaches that are cost-effective for on-farm benchmarking. In the future, collaborative research approaches could be used to co-develop indicators that explicitly link to soil functions and farmer decision-making in the field, working with advisors (such as Niels Corfield and Nick Padwick) and involving the academic soil science community (such as Sacha Mooney and Andy Neal, who attended the Future of Farming conference). Stakeholders scored this as a normal level of priority.

---

[79] https://oifdata.defra.gov.uk/

[80] For more information see soil health projects funded by the Defra Farming Innovation Programme https://www.ukri.org/news/funding-boosts-farm-resilience/

[81] https://bofin.org.uk/truthproject/

4.2 Impacts of soil biology on weed populations (esp. blackgrass)

The link between soil biological properties and weed populations is a novel area of research with little peer-reviewed information currently available. A simple search on the Web of Science using the search terms "weeds", "soil health", and "microbiology" identified 21 publications; however, most of these were not directly relevant to this topic (see Table 23). The mechanisms through which a healthy soil microbiome might control weeds are complex and may be direct or indirect. These include creating a healthy, fertile soil that promotes the cash crop's growth and allows indirect suppression of weeds through competition. Soil microorganisms may also facilitate the breakdown of crop residues that suppress weed growth through allelopathy – another indirect effect of healthy soil biology. But soil biology may also directly affect weed growth through the degradation of weed seeds in the soil; this may be the case, particularly for fungi in soils (Gómez et al. 2014). Researchers have also explored the potential to identify products of soil microbial metabolism that may inhibit seed germination for pre-emergent herbicide development, or for arrestment of weed growth post-emergent (Kao-Kniffin et al. 2013).

Cheng et al. (2022) reviewed opportunities for microbiome suppression of weeds (see summary in Figure 7). While two of the methods they discuss are essentially alternatives to herbicides (microorganisms formulated as bioherbicides or application of the compounds produced by microorganisms that suppress weed growth), they also discuss field management practices (integrated weed management) that enhance microbiome function for weed suppression. It is this third method that is particularly interesting to regenerative farmers who are aiming to build healthy soils with healthy microbial populations to suppress weeds.

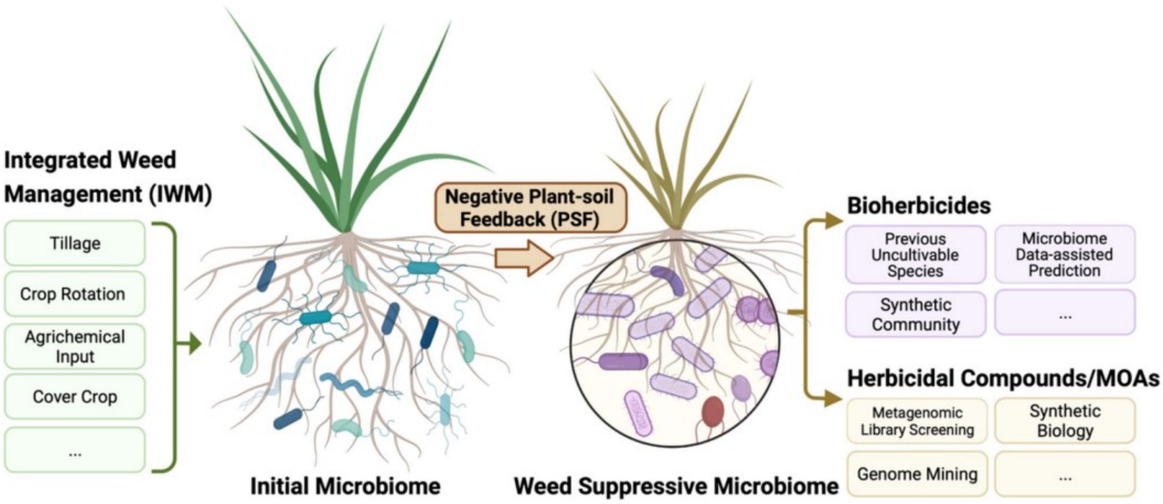
Some mechanisms for microbiome suppression of weeds described by Cheng et al (2022) include:

1. Manipulation of the soil microbiome to create a weed-suppressive soil; although, the characteristics of a weed-suppressive microbiome are not yet defined. This may include promotion of microorganisms that produce weed-suppressive compounds as mentioned above. The challenge with this approach will be to shift natural populations of microorganisms towards communities with sufficient numbers of suppressive microorganisms to have a real impact on weed populations. More research is needed to characterise microbiomes in soils that have lower incidence of weeds and to identify management strategies to promote these communities.
2. The use of soil microorganisms to immobilize excess nutrients that promote weed growth has been proposed as a strategy for weed suppression. The process of

nitrogen immobilization through the addition of high-carbon materials, such as wood chips, is well-documented. Cheng et al. (2022) suggest that this approach can be managed to limit nutrient availability during periods when weed proliferation is most likely. However, the challenge lies in balancing the nutrient needs of the crop while restricting access to weeds. This concept may underlie the regenerative agriculture community's belief that fungal-dominated soils suppress weed growth. Soils receiving significant inputs of woody material may foster unique fungal communities, but weed suppression in these soils may be less about direct fungal action and more about the role fungi play in immobilizing excess nutrients.

3. Finally, Cheng et al. (2022) propose more research into plant-soil feedback (PSF) which occurs when a plant species alters biotic or abiotic conditions in the soil, thereby affecting growth of the same species, or a different species. Negative feedback where plant growth is inhibited can be due to allelopathic effects or accumulated host-specific pathogens. Some evidence that PSF controls weeds has been gathered in studies of invasive plants that appear to be more effective at colonising areas where they are not native because the microbiome that normally suppresses their spread through PSF, is not present in the invaded regions.

Figure 7 Schematic diagram illustrating approaches to harnessing the soil microbiome and negative plant-soil feedback to improve weed management in regenerative agriculture (copied from Cheng et al. 2022)



A more direct mechanism for weed suppression by active soil microbial populations could be through decay of weed seeds by soil organisms. Management practices that facilitate this decay can contribute to a reduction in the size of the weed seedbank thus being a key tool for integrated weed management (Pollard 2018). Gómez et al. (2014) tested the hypothesis that diversified cropping systems would have a more active microbial population effective at reducing the weed seedbank through seed decay. They highlighted the complexity of factors affecting seed survival in the soil including the environment, the weed seed and the pathogen (soil organism decaying the seed). In their study they found considerable amounts of decay of Giant Foxtail seeds after 12 months buried in soils in a diverse (4-year) rotation compared with a less diverse (2-year) rotation. However, this effect was only apparent in one year, demonstrating that environmental conditions are also important factors affecting weed seed decay. Nikolić et al. (2020) tested the hypothesis that weed seed decay would be greater in an undisturbed buffer area of the field than in the no-till cropped area. They were surprised to find that seed decay was much higher in the no-till area of the field; they also reported much higher activity of cellulolytic microorganisms associated with decay in the no-till field, confirming that the microbial community under no-till is more adapted to decay functions. This provides some preliminary evidence that manipulation of the microbiome through crop management practices, including tillage, may be used to create more weed suppressive soils.

Gómez et al. (2014) went on to identify a relationship between weed seed decay and the fungal genus *Pythium*. Other fungal groups responsible for weed seed decay have been identified, e.g. species from the Phylum *Ascomycota* such as *Chaetomium globosum* and *Cephaliophora tropica* (Chee-Sanford 2008). Bacteria may also contribute to weed seed decay, e.g. *Pseudomonas fluorescens* has been reported to reduce populations of downy brome seeds (Pollard 2018). There has been particular interest in the fungal isolate *Fusarium avenaceum* isolate F.a.1 which has been proven to be effective in decay of Wild oat seeds (Pollard 2018; Lewis et al. 2022).

We are not aware of any current projects in the UK that are exploring these microbiome routes to weed control. The connections between soil biology and weed populations are still not well understood and this topic was scored as a high priority for future research. Diverse cropping systems may influence soil biology and allelopathy, which may suppress weed populations (see challenges 2.7 and 2.8). This research will require a multidisciplinary approach spanning weed science, ecology, toxicology, soil microbiology and plant physiology that includes on-farm studies and fundamental biology.

4.3 Mob grazing[82] impacts on soil health

Mob grazing is a term used to describe a range of management techniques that involve relatively frequent movement of grazing animals between paddocks with sward entry heights and exit heights taller than traditional set stocking or rotational grazing systems. The terminology describing these systems is varied which makes it challenging to identify evidence from peer-reviewed and grey literature. We used a variety of terms (mob grazing, multi-paddock grazing, cell grazing, intensive rotational grazing, holistic planned grazing, management intensive grazing) in our literature search to identify papers which have studied what is broadly understood to be mob grazing in the regen ag community. Only 17 papers linking mob grazing and soil health were identified, with just 3 of these published in the UK (see Table 23).

Jordon et al. (2024) provide a good summary of the current understanding of impacts of grazing specifically on soil carbon with a focus on sequestration of carbon and mitigation of emissions. They explain the challenges with making generalised statements about grazing impacts on soil carbon in light of the variations in the soil's chemical and physical composition, the local environment, and how the soil is managed. They also point out how rates of carbon sequestration will vary depending on the starting point, i.e. soils that are degraded and low in carbon will build carbon at a much faster rate than soils that are already nearly saturated with carbon. They add that any soil carbon sequestration in a grazed system needs to be stacked up against the emissions of methane from the livestock grazing that land. And finally, they point out that comparisons need to be made with systems without livestock that may capture more carbon (e.g. forested landscapes). Their paper sets out to scrutinise some of the "remarkable claims about the extent to which anthropogenic carbon emissions may be mitigated by sequestration in pastures and rangeland" being made "outside the scientific mainstream".

Jordon et al. (2024) report that approximately 80% of European grassland soils are below their carbon saturation point, suggesting that there is potential through improved management to build carbon in these soils. However, they also report that the scientific evidence base for the relative effects of different pasture management regimes on soil carbon is limited and argue that more medium- and long-term studies are needed. In general, they predict gains in soil carbon on improved pastures in the UK if rotational grazing is used compared to set stocking, but find that the evidence base

[82] Since mob grazing is not very clearly defined, synonyms were generated using ChatGPT. These were: High-density grazing, Adaptive multi-paddock grazing, Cell grazing, Intensive rotational grazing, Holistic planned grazing, Management-intensive grazing (MIG)

for claims about benefits from mob grazing (e.g. trampling of grass into the soil surface can increase soil organic matter in the topsoil) is limited and requires further research.

Some of the “remarkable claims” referred to by Jordon et al. (2024) are based on studies like the ones summarised in Table 8, but these results should be interpreted with caution. Of these seven studies, only one was conducted in the UK, so environmental conditions are quite different from here. Several studies compare types of intensive grazing, such as Management Intensive Grazing or multi-paddock grazing, with arable cropland (Machmuller et al. 2015; Shawver et al. 2021; Trimarco et al. 2023). As a result, their findings reflect not only the effects of grazing management but also the impact of shifting land use from cropland to grassland. The UK study by Trickett and Warner (2022) compares grazed and ungrazed ley phases, so also can’t be used to build the evidence base for mob grazing specifically. Both Mosier et al. (2021) and Teague et al. (2011) compare continuous grazing with multi-paddock systems and report improvements in various soil health parameters. Mosier et al. (2021) found not only higher total carbon stocks but also higher proportions of carbon in the stable mineral-associated fraction in the AMP system. However, in both of these studies it is not clear if the tall grass and frequent movements of livestock is necessary to result in these improvements, since there are no comparisons with less intensive rotational grazing systems. The study by Díaz de Otálora et al. (2021) is more useful since it compares two rotational grazing systems, one of which is “regenerative”. They found increases in soil C in regenerative grazing systems, but no other indicators of soil health differed between the two grazing management approaches. While this finding is valuable, the environmental conditions in northern Spain differ significantly from those in the UK, which may limit the direct applicability of the results to UK contexts.

In the UK there have also been several projects recently that studied mob grazing (e.g. SEEGSLIP[83], Mob grazing: Impacts, benefits and trade-offs[84], Rothamsted cell grazing[85], Harper Adams review of mob or holistic grazing[86]). Some of these have

---

[83] See Wagner et al. 2023 and other papers available through the project website: https://www.ceh.ac.uk/our-science/projects/seegslip-results

[84] https://farmpep.net/project/mob-grazing-defra-project

[85] https://www.rothamsted.ac.uk/news/cell-grazing-supports-double-livestock-hectare-set-stocking-and-delivers-environmental

[86] https://www.harper-adams.ac.uk/research/project/1331/review-of-the-value-of-mob-or-holistic-grazing-regimes-used-to-support-management-of-historic-and-ecological-assets

included literature reviews, but none of these are publicly available yet. The Rothamsted cell grazing interim project report has recently been published. This project compares cell grazing (using TechnoGrazingTM infrastructure where animals were moved every 1-2 days to new pasture with the area allocated varied to suit desired recovery periods) and set stocking at the North Wyke research farm in West Devon. The project found increases in soil carbon contents due to cell grazing and no differences in compaction between the two systems.

There is also a new PhD project at SRUC: "Is mob grazing beneficial to soil health and the environment?" which will be a source of valuable and detailed information on soil carbon changes under mob grazing in the Scottish environment.

Table 8 Rapid summary of outcomes from peer-reviewed literature on mob grazing or related systems

Study type	Systems compared	Study location	Parameters measured	Outcome	Authors
Experiment	Conventional rotational grazing (6-10 d grazing, 15 d rest) vs Regenerative rotational grazing (1-2 d grazing, 24 d rest)	Northern Spain	Topsoil organic carbon, six enzymes (β-glucosidase, β-glucosaminidase, sulfatase, acid phosphatase, *L*-alanine aminopeptidase, and *L*-leucine aminopeptidase), simplified water retention index, biodiversity via 16S rRNA metabarcoding of soil prokaryotes.	Topsoil carbon significantly higher in regenerative system, no other parameters differed between the two systems	De Otalora et al, 2021
Field survey	Chronosequence of three sites following conversion to management intensive grazing from intensive arable system	Georgia, USA	Carbon stocks in top 30 cm of soil, cation exchange capacity (CEC), water holding capacity (WHC)	Clear increase in carbon stocks (75% increase over the starting value of 0.5% C) in first six years; plateau in carbon after 6.5 years; increased CEC by 95% and WHC by 35%	Machmuller et al. 2015
Field survey	"over-the-fence" study comparing adaptive multi-paddock grazing (AMP; rest:grazed day ratio >40) vs conventional grazing	Kentucky & Mississippi, USA	Organic carbon and nitrogen stocks to 1 m, dissolved organic matter (DOM), light particulate organic matter (LPOM), heavy particulate organic matter, (HPOM) mineral associated organic matter (MAOM)	13% more organic carbon and 8% more total nitrogen stocks to 1 m on AMP grazing fields; 25% more C in the MAOM fraction and 15% more C in the HPOM fraction for AMP grazing fields	Mosier et al 2021
Field survey	Monitored soil health over time (2 years; 2017, 2018) in a field converted from cropland	Colorado, USA	Bulk density (BD), water-stable aggregates, soil organic C (SOC), microbial biomass C, potentially mineralizable N (PMN), and β-	Significant increase over time for: BG, MBC, PMN, pH, K; significant increase (negative effect) over time for BD and decrease for P	Shawver et al. 2021

	to irrigated Management Intensive Grazing (MiG)		glucosidase (BG) activity, pH, EC, plant-available K and P; 0-5 cm and 5-15 cm depths		
Field survey	Follow-up study to Shawver et al. (2021) Monitored soil health over time (2 years; 2021, 2022) in a field converted from cropland to irrigated Management Intensive Grazing (MiG)	Colorado, USA	Bulk density (BD), water-stable aggregates, soil organic C (SOC), microbial biomass C, potentially mineralizable N (PMN), and β-glucosidase (BG) activity, pH, EC, plant-available K and P; 0-5 cm and 5-15 cm depths	Increase in BD over time; improved aggregate stability; increases in BG activity, MBC, SOC, general increase in soil biological and chemical health index,	Trimarco et al 2023
Field survey	Compared light continuous grazing (LC; n = 3); heavy continuous grazing (HC; n = 3); and planned multi-paddock rotational grazing (MP; n = 3) management	Texas, USA	Bulk density, resistance to penetration, aggregate stability, hydraulic conductivity, water infiltration, nitrate, ammonium, total N, organic matter, soil food web analysis (total & active bacteria and fungi, AMF infection, nematodes, protozoa, fungal:bacteria (F:B) ratio	Aggregate stability, resistance to penetration better with MP vs HC; Higher SOM, CEC MP vs HC; higher F:B ratio in MP vs HC	Teague et al. 2011
Field survey	Mob grazing a three-year grass-clover ley vs ungrazed three-year grass-clover ley	Hertfordshire, UK	Earthworm counts, soil organic matter	Higher earthworm counts in mob grazing compared to ungrazed, particularly the juveniles and endogeic species	Trickett & Warner 2022

There is still insufficient evidence to demonstrate that intensive rotational grazing systems such as mob grazing result in improvements in soil health relative to less intensive rotational grazing systems. There is clearly a spectrum of regenerative grazing practices with variations in frequencies of livestock movement, and entry and exit sward heights, that interact with factors like sward composition and local environmental conditions to affect soil health. Moving from set stocking to some sort of rotational system is advisable to improve soil health, but further research is needed to determine which combinations of management factors are most effective to optimise soil health under rotational grazing management. The Pasture Fed Livestock Association engages actively with the research community to provide study sites for research. They should be involved with plans for future projects that should also take into account results from the ongoing studies funded by Defra and Natural England.

Although the focus of the review was on plant/soil science, this topic was included because arable farmers may seek to integrate livestock into their systems (see challenge 2.9). It was ranked as a high/normal in priority requiring applied research. It's worth noting that ADAS is currently conducting a trial exploring this question at various sites across the UK, which may provide a clearer answer in the near future.

4.4 Impacts of biostimulants on (plant and) soil health

Biostimulants are a broad category of crop inputs that can be defined as products that stimulate plant nutrition processes independently of the product's nutrient content with the aim of improving one or more of the following characteristics: nutrient efficiency, tolerance to abiotic stress, and/or quality (Storer and Berdini 2022). They can be broadly divided into non-microbial (e.g. seaweed extracts, humic substances, chitin and chitosan derivatives) and microbial (e.g. plant growth promoting rhizobacteria AKA PGPR, arbuscular mycorrhizal fungi AKA AMF) products. Biostimulants have attracted a lot of interest among the regen ag community as alternatives to fertilisers or pesticide. There are a wide number of commercial products currently on the market in the UK and many regenerative farmers are also producing their own biostimulants on-farm (e.g. compost teas, compost extracts, plant ferments). In 2016 the AHDB commissioned a review of the function, efficacy and value of biostimulant products available for UK cereals and oilseeds (Storer et al. 2016). In 2022 a further review on biostimulants was commissioned by Defra (Storer and Berdini 2022). These two documents comprehensively review the evidence base for commercially available products and make some recommendations. Storer and Berdeni (2022) identified 12 categories of biostimulant with new peer-reviewed evidence available since 2016.

These included: Seaweed extracts (28 studies), Nitrophenol based (10), Humic acids (9), Fulvic acids (7), Amino acids (5), Mixtures (5), Glutacetine (4), Plant growth promoting bacterial (3), Synthetics of chemicals (2), Protein hydrolysates (2), Microalgae (1), Cyanobacteria (1). Their REA found evidence that 8 of the 12 biostimulant products can benefit arable and field grown horticultural crops, primarily in terms of growth or yield. The strongest positive effects were for amino acids, seaweed extracts, humic and fulvic acids (mixed) and nitrophenol based biostimulants. For other products results were either mixed (both positive and negative results reported) or the evidence was not from field studies (tested mainly in controlled environments) and therefore was not deemed as strong. Recommendations for future research and development priorities from this report were:

1. Conduct more testing of biostimulant efficacy under field conditions
2. Develop a standardised method of defining and measuring nutrient uptake, nutrient use efficiency and tolerance to abiotic stresses.
3. Provide end users with specific guidelines about how best to target biostimulant products
4. Investigate the evidence for economic benefit of biostimulant use.
5. Explore impacts of biostimulants on crop disease or pest tolerance/safety and if any products have any other additional effects outside those reviewed in the REA[87]
6. Build the evidence base on human and environmental safety of the biostimulants

We would add a need to build up the mechanistic understanding of how these products work so that users can make informed decisions about the best product to use for their environmental and management context.

Alongside the growing interest in commercial biostimulant products, many farmers are experimenting with producing biostimulants on their own farms through various methods for producing compost teas (both aerated and non-aerated mixtures of compost fermented with water and filtered Litterick et al.2004), compost extracts (filtered products of compost mixed with any solvent, but not fermented Litterick et al 2004), and/or seed treatments (e.g. controlled microbial compost seed dressings). A review was conducted about 20 years ago by UK-based scientists to evaluate the evidence for a range of organic products, including compost extracts and teas (Litterick

[87] The REA focused on: 1) Crop growth, yield and economics, 2) Crop quality, 3) Nutrient use efficiency, 4) Stress tolerance, 5) Human health and safety, 6) Environmental safety

et al. 2004). They reported some suppression of plant diseases by compost teas applied in the glasshouse and in field grown edible and ornamental crops. This benefit of compost teas has also been reported in more recent reviews (e.g. Sharma et al. 2024). Competition and disease suppression by microorganisms present in the teas has been proposed as the mechanism for disease suppression, as well as induced resistance and antibiosis[88] (Curadelli et al. 2023).

Recent interest in compost teas among the farmi ng community has grown out of interest in soil microbial conditions and particularly fungal and bacterial communities. Passive aeration methods popularised by Dr. David Johnson and Hui-Chun Su at New Mexico State University. The Johnson-Su system is designed to produce a compost with a relatively high population of fungal organisms. This compost is used to make a fungal-rich tea for application to the soil with the goal of shifting the soil microbial community towards a more "fungal-dominant" community. Many regenerative farmers subscribe to the theory that fungal dominant soils are important for maintenance of soil health and crop productivity (e.g. as advocated by Dr. Elaine Ingham[89]); the evidence and research needs linked to this are discussed in more detail throughout this Challenge section on soil health.

The Soil Association ran an Innovative Farmers Field Lab on compost teas in 2017/2018 and results were inconclusive with increased yields in some cases but no measurable changes in soil microbial communities due to the addition of compost tea[90]. More recently Curadelli et al. (2023) conducted a meta-analysis on the evidence for yield promotion from compost teas; they found a slight yield benefit from added compost teas relative to a water control in 8 observation pairs, but negative effects from the very small sample set where compost tea was compared to conventional fertilisers.

O'Neill and Ramos-Abensur (2022)provide a detailed review of liquid ferments used in the Andes which bear some similarities to the homemade biostimulants used in the UK. Farmers in the Andes make liquid ferments using manure as the main component, but vary widely in terms of additional ingredients, such as molasses, rock dust, urine, wood ash, guano, plant biomass, and various minerals and salts, prepared in simple containers. Manure fermentation may be combined with locally sourced microbial inoculants, or with mineral preparations similar to those prescribed for more

---

[88] Production of antibiotics or toxic compounds that inhibit or kill competing microbial species.

[89] https://www.soilfoodweb.com/

[90] Reports available here: https://innovativefarmers.org/field-labs/compost-teas-in-arable-cropping-2nd-trial/

conventional foliar fertilizers. Many fermented liquid fertilisers also have added "effective microorganisms" or EM[91] which were developed in Asia for use in anaerobic methods of compost production (i.e. Bokashi). Much of the lore around the benefits of liquid ferments (including compost teas) attributes any plant growth promotion to their microbial properties, but the review by O'Neill and Ramos-Abensur (2022) could not find any evidence that demonstrated a positive impact on plant growth due specifically to microbes found in manure-based ferments that was clearly distinct from the effect of added plant nutrients in ferments. Or to put it more simply: benefits from manure-based ferments appear to be due to the nutrients they supply, not the added microorganisms. Future research testing the efficacy of liquid ferments, compost teas, etc, should include treatments that provide similar concentrations of nutrients without the microorganisms present to verify the reasons for any observed plant growth promotion.

Controlled Microbial Compost (commonly known as "Luebke compost") is produced by mixing an organic waste source with basalt or rock dust, 10% finished compost by volume, 10% clay loam and a proprietary inoculant: CMC Compost Starter®, a mixed culture of 55 different types of microbes. CMC is turned frequently (typically more than 20 times in six weeks). The finished compost may be used as a seed dressing (thus acting as another type of biostimulant). The CMC Compost Starter® itself can be used as a spray on fields of green manure to hasten breakdown of plant residues. The Organic Research Centre is currently conducting a literature review on a variety of novel composting methods and use of the products as biostimulants; this will help to shape future research activities on biostimulants.

There's a wide array of commercial biostimulant products available in the UK market, and many regenerative farmers are also producing their own biostimulants on-farm, such as compost teas, compost extracts, and plant ferments. However, evidence of efficacy for many of these products remains inconclusive. European lawmakers included plant biostimulants in the new EU Fertilising Products Regulation that came into force in July 2019. The Regulation requires conformity assessment so that plant biostimulants should have the effect claimed on their labels. Defra are currently running a 3-year project to determine how the regulations should be applied in the UK. There are also some concerns about unexpected side effects of applications on soil biology. Applied research with farmers could be used to support knowledge exchange about the benefits and

[91] To add to the complexity of systems and terminology, these are sometimes referred to as "efficient microorganisms", e.g. as in the paper by Singh et al. 2011

limitations of these products in real-world conditions; this is a normal level of priority for stakeholders.

4.5 Impacts of strategic (occasional) tillage vs glyphosate on soil health

Minimising soil disturbance, often interpreted as no tillage at all, is one of the key principles of regenerative agriculture. But there remain questions about the long-term impacts of this practice on soil health, the environment, and agronomic productivity; no-till practices can lead to soil compaction, greenhouse gas emissions and reduced yields in some environments (Van den Putte et al. 2010; Pittelkow et al. 2015; Blanco-Canqui and Wortmann 2020). No-till systems are reliant largely on the use of the herbicide glyphosate, which raises concerns about the development of herbicide-tolerant weeds and also the effects of the herbicide on soil biological health (Nguyen et al. 2016). In the UK, the use of no-till practices has been linked with the build-up of certain weed species, e.g. blackgrass. On the other hand, no-till practices result in the accumulation of soil carbon in surface layers and have been linked with many positive outcomes for soil health (Ogle et al. 2012). No-till systems protect the soil surface from water and wind erosion and have a positive effect on the water cycle at the catchment scale through increased infiltration. In addition, reductions in tillage reduce energy and labour use on farms (Powlson et al. 2014)

In spite of these benefits, some practitioners, especially organic farmers, continue to plough periodically to destroy cover crops and ley phases without herbicides, for weed control, and to incorporate organic manures (Cooper et al. 2016). There may also be a need to use mechanical methods like subsoiling to address soil compaction periodically even on regenerative farms (Blanco-Canqui and Wortmann 2020).

This dichotomy in practices has led to an interest in assessing the relative effects of no-till systems that are reliant on glyphosate compared with systems that use occasional "strategic" tillage to address soil compaction issues or to manage weeds and residues (e.g. in organic systems).

"Strategic" or "occasional" tillage is one area that has not been studied extensively under UK conditions. There have been about 100 papers published that use these terms; about a third of these are from Australia, with only one UK publication. Peixoto et al. (2020) published a useful global meta-analysis on this topic in 2020. They selected papers that did <u>not</u> use "rotational tillage" i.e. regularly scheduled tillage events, but instead focused on studies that used tillage to address a specific problem, most often soil compaction, but sometimes weed control or incorporation of residues. Figure 8 summarises the key messages from the paper and shows that impacts of occasional tillage on most variables were positive or neutral, with the only negative effect on soil carbon for plough/harrow interventions. This suggests that occasional tillage can be used with minimal negative effects, but there have been no systematic studies on this in the UK; more research is needed to confirm how strategic tillage could be implemented to address some challenges i.e. with weeds and compaction, while minimising negative impacts on soil health and C sequestration.

In addition to peer-reviewed studies, Defra has funded various studies over the years that have included tillage practices (Table 9). There are also various ongoing trials where tillage system is a factor (Table 10). It is therefore important to build on the existing knowledge and not duplicate existing projects and experiments when designing new studies on this topic.

Figure 8 Graphical abstract from Peixoto et al (2020) showing positive (+), negative (-) and no (=) effects of three tillage methods on weeds, soil properties and crop yields

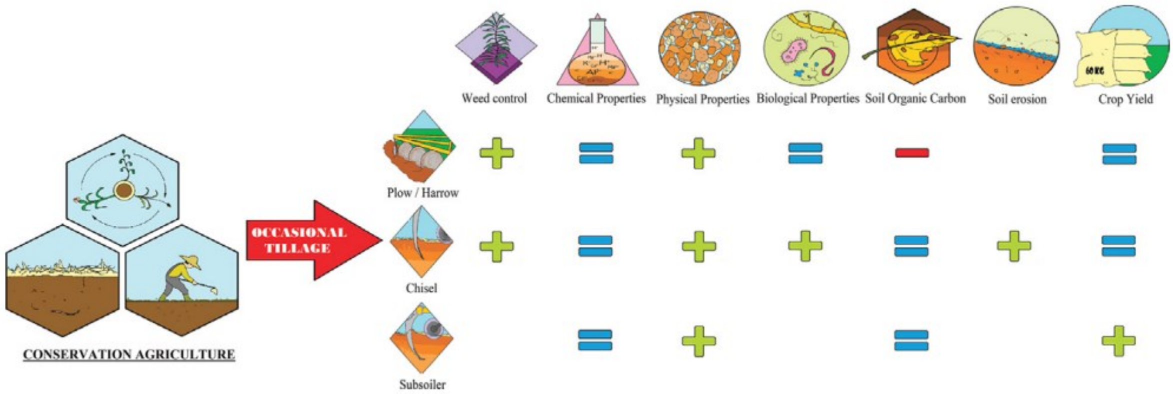


Table 9 Some historic Defra projects that included tillage practices under UK conditions

Project Code	Title	Completion year
WT15100	DTC Phase Final Report	2019
SP0513	The development of national guidelines for sustainable soil management through improved tillage practices - SP0513	2001
SP0561	The effects of reduced tillage practices and organic material additions on the carbon content of arable soils - SP0561	2007
OF0392	CORE 2: Reduced tillage and green manures for sustainable organic cropping systems (TILMAN-ORG)	2014
AR0407	Modelling weed crop dynamics and competition to improve long-term weed management - AR0407	2005
LK0923	Improving crop profitability by using minimum cultivation and exploiting grass weed ecology. - LK0923	2005

Table 10 Summary of ongoing projects studying strategies to reduce tillage intensity in arable systems in the UK

Name	Lead Organisation
The Allerton Project	Game & Wildlife Conservation Trust
McCain Smart & Sustainable Farming Programme	McCain's
Strategic Cereal Farm North (David Blacker)	AHDB
Sustainability Trial for Arable Rotations (STAR)	NIAB
Centre for High Carbon Capture	NIAB
New Farming Systems (NFS) Project	NIAB
Leeds University regen ag trial (Fix our Food)	Leeds University
Large-scale Rotation Experiment	Rothamsted Research
Nafferton Factorial Systems Comparison experiment	Newcastle University

The effects of glyphosate use on soil health and the wider environment remain highly topical. In 2016 The Soil Association published a summary of the evidence to date on impacts of glyphosate on soil health. They concluded that the evidence was “far from conclusive” (Soil Association 2016) and recommended further research looking at a range of groups of soil fauna, the effects of other ingredients included in formulations, and the fate of the breakdown products of glyphosate e.g. aminomethylphosphonic acid or AMPA.

A Web of Science search using the search terms ("soil biology" OR "soil health" OR "soil fungi" OR "soil bacteria" OR "soil biodiversity") AND (glyphosate" OR "Round-Up") in the topic field identified 143 peer-reviewed articles on the topic as of October 2024 (Table 23). These include laboratory, greenhouse and field studies using a range of application rates and frequencies and assessing effects on microflora (fungi, bacteria), soil fauna, and general microbial biomass and respiration. Conducting a review of this evidence base is beyond the scope of this review, but the meta-analysis by Nguyen et al. (2016) is a useful summary of many studies. These include field and laboratory experiments with treatments designed to replicate farm practice (dose rates <10 mg a.i./kg soil) as well as others designed to determine effect endpoints for ecotoxicology purposes (>100 mg a.i./kg soil). A quick survey of farmers on X (26 Oct 2024) returned typical application rates of 700-1000 g a.i./ha which translates to <2 mg a.i./kg soil using the assumptions in the paper. Figure 9 shows that in this meta-analysis rates typical for UK arable farmers had no effect on soil microbial respiration or biomass, both of which are useful indicators of general soil biological health. The meta-analysis concludes by stating that “generalisations about the toxicity or safety of glyphosate to SMR (soil microbial respiration) and SMB (soil microbial biomass) should be qualified with details of the conditions under which glyphosate is applied”.

This conclusion highlights a common challenge in designing research to compare the impacts of tillage and herbicide-based weed control on soil biology: there are multiple factors which influence the behaviour and impacts of glyphosate or tillage on soil biology. Field soil health is shaped by a mixture of management and environmental factors, many of which are integral to regenerative systems, such as diverse crops, organic matter inputs, and livestock grazing. Likewise, in tillage-based systems like organic farming, various other practices are used which may interact to affect soil biology. Reductionist methods, which do not include these interactions and reduce complex systems into individual components to determine cause and effect, will not produce outcomes that reflect what happens in the real world. Because of this challenge, we recommend using farming system studies to better understand the tradeoffs between herbicide-based weed control and tillage, in the background of regenerative farming practices.

Table 11 illustrates in a simplified way four different systems that could be compared when designing farming systems studies to assess impacts of herbicides and tillage on soil biological health. Systems 2 and 4 are both managed with herbicides but differ in the use of tillage for seed-bed preparation, incorporation of residues and some weed control. Comparisons between these systems are frequently reported in the literature. Van den Putte et al. (2010) conducted a meta-regression on impacts of conservation agriculture on crop yields in Europe, which concluded that there were reductions (on average 8.5%) in crop yields when the system is implemented in European environments, but that this depended on crop type, tillage technique, texture of the upper soil layer and crop rotation. Pittelkow et al.'s meta-analysis (2015) on conservation agriculture globally, highlighted the importance of including all three components of that system (no tillage, residue retention and crop rotation) in order to avoid reductions in yield. Numerous authors have reported on the potential to increase topsoil carbon in no-till systems; Ogle et al. (2012) compiled 74 published studies comparing no-till and deep tillage for their meta-analysis.

Figure 9 Figure extracted from Nguyen et al. (2019) illustrating the effects of glyphosate on soil microbial respiration (SMR) and soil microbial biomass (SMB) at different rates of glyphosate application. Results of a meta-analysis including field and pot trials.

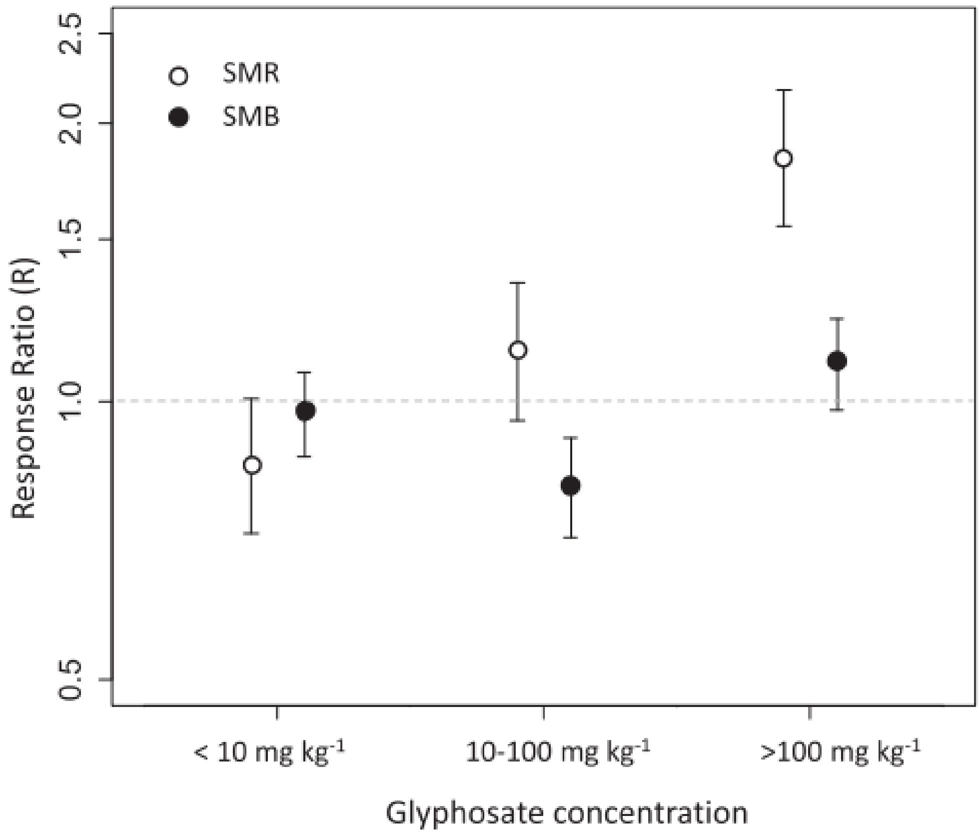


Fig. 3. The impact of glyphosate concentration categories on soil microbial respiration (SMR, open circles) and soil microbial biomass (SMB, filled circles). Error bars represent 95% confidence levels. The dashed horizontal line represents the no effect level. Values above the horizontal line demonstrate increased respiration in response to a glyphosate application, whereas values below the horizontal line demonstrate reduced respiration.

Table 11 Representation of the four different systems (1-4) that emerge when combining +/- herbicide and +/-tillage in farming system comparisons

	Organic	Conventional
Tilled	1. Tillage-based organic farming; herbicide-free	2. Tillage-based conventional farming; with herbicides
No-till	3. No-till organic farming; herbicide free	4. No-till conventional farming/conservation agriculture/ “regenerative” agriculture; with herbicides

Organic and conventional systems (1 vs 2 in Table 11) are frequently compared using survey and experimental approaches. These comparisons are often done to assess differences in yields (Seufert et al. 2012; Ponisio et al. 2015). Impacts on soil health have been reported particularly using the DOK trial in Switzerland which compares biodynamic, organic and conventional systems of farming (Fließbach et al. 2007; Esperschütz et al. 2007; Joergensen et al. 2010; Mayer et al. 2022; Krause et al. 2022). In the UK, the Nafferton Factorial Comparisons Trials (also known as "QLIF") compare organic and conventional production systems. More recently a tillage treatment has been included as an experimental factor (Orr et al. 2011, 2012). Gattinger et al. (2012) conducted a meta-analysis to assess differences in soil C between organic and conventional systems.

Studies comparing the effects of tillage in organic systems only (1 vs 3 in Table 11) are not common, but this was the focus of the TILMAN-ORG[92] project which the Organic Research Centre and Newcastle University in the UK delivered in collaboration with European partners. As part of the TILMAN-ORG project Cooper et al. (2016) conducted a meta-analysis on the effects of reduced tillage intensity on crop yields in organic systems; they concluded that shallow non-inversion tillage minimised yield reductions while still preserving positive effects on soil carbon.

There is a gap in studies that compare system 1 (organic, tillage-based) with system 4 (conventional regenerative). There is also a lack of information on strategic or occasional tillage in no-till systems in the UK. Future research efforts could use one of the following approaches:

1. Surveys could be conducted comparing organic tillage-based systems with regenerative systems in the same region with similar soil types. The surveys could record a range of indicators of soil health (regenerative outcomes) and agronomic outcomes. Detailed explanatory data would need to be collected on land and crop management (including inputs, crop varieties, field activities) as well as data on the local environment (soil properties, weather). Frequency and depth of tillage could be included to explore the effects of strategic tillage. This information could be analysed using multivariate or other advanced statistical modelling methods to tease out the key factors driving differences in soil health. Impacts of glyphosate, as well as other management practices could be elucidated using this approach.

92 https://www.tilman-org.net/tilman-org-home-news.html

2. Identifying long-term trials with this comparison; to our knowledge, only the Nafferton trials at Newcastle include a fully organic treatment contrasted with ploughed and direct drill conventional management, in the same field. Securing long-term funding for any trials is always a challenge. Strategies to address this funding need, as well as the challenges of staff continuity, need to be devised.

There are lingering questions regarding the long-term effects of reduced tillage intensity on soil health, the environment, and agronomic productivity. This issue was highlighted and added to the list of challenges at the workshop. While periodic cultivation can address some of these concerns, it remains unclear how this occasional "strategic" tillage impacts ecosystem health and crop production. Additionally, the environmental impacts of strategic tillage compared with the use of glyphosate for weed control are poorly understood (a key question raised by Andy Cato and Andy Neal at the Future of Agriculture conference). This is a high-priority area for applied research. The focus should be to explore the impacts of no-till systems with glyphosate compared with systems using no glyphosate but with occasional/strategic tillage (including more intensively tilled organic systems) across the breadth of agronomic and environmental indicators. This research will provide better guidance on the most effective ways to implement regenerative agriculture practices in the UK environment.

Challenge 5: Wider system considerations

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[93] (EIP). 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

[93] https://www.gov.uk/government/publications/environmental-improvement-plan

through changes to farming practice, but the evidence base is needed to support policy.

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

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 (Table 24). 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 section 2.2). Living mulch systems (see section 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 (Table 24); 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 12 will provide useful background information on the impacts of legumes within regenerative rotations on GHG emissions. The ongoing projects in Table 13 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 12 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 13 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 (Table 24). 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[94] and H3 (Healthy Soil, Food, People)[95] 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

---

[94] https://fixourfood.org/

[95] https://h3.ac.uk/

(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 considerable 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 10.

Figure 10 Detailed illustration of three levels of monitoring networks for agroecology/regenerative agriculture copied from Burgess et al. (2023)

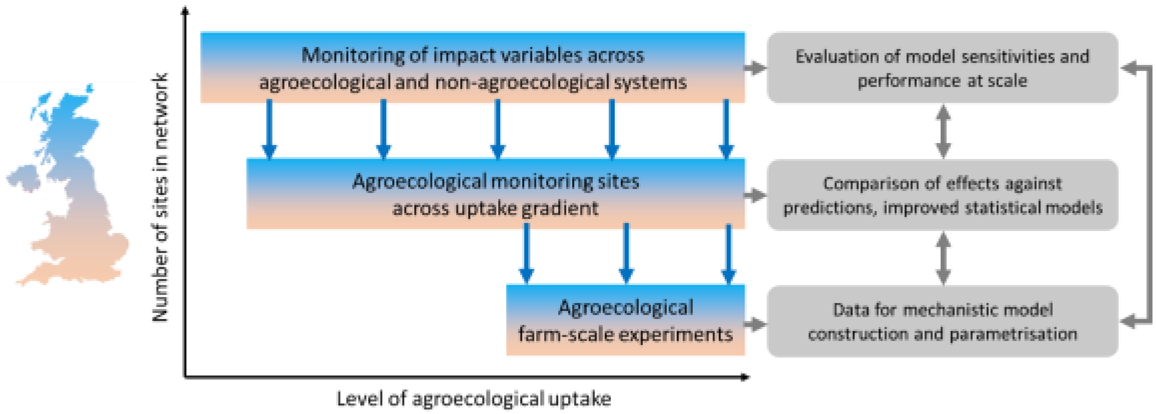


Figure 7. Schematic illustration of three levels of monitoring networks for agroecology (coloured boxes) and their potential use for agroecological modelling (grey boxes). The levels vary in their coverage of the agroecological uptake gradient and the number of sites in the network (as determined by 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.

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 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 Section 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[96].

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[97] 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 project[98] (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.

[96]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.

[97] https://healthyminorcereals.eu/en/about-project/objectives

[98] 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 (Table 25).

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 B_9 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 (Section 3.7) and plant populations (Section 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[99] (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[100] includes 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 1.2 above). 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

---

[99] https://h3.ac.uk/

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

question. More basic research is needed to clearly define "nutrient density". This topic was ranked as high to normal priority by workshop stakeholders.

Challenge 6: Socioeconomics

6.1 Impact (and the factors affecting it) of regenerative agriculture systems on farm livelihoods

There is a lack of hard data on the financial viability of regenerative agricultural practices across the spectrum of environments and cropping systems where they may be implemented in the UK. This has been identified as an area of uncertainty and a barrier to uptake of regen ag by respondents in surveys (see details in Section 6.2). It is reasonable to expect some reductions in individual crop yields when regenerative agriculture practices are introduced, based on peer-reviewed studies that have looked specifically at yield reductions from conservation agriculture/reduced tillage intensity. The study by Van den Putte et al. (2010) focused on northern Europe is most relevant to UK conditions. They used a meta-analysis approach to assess yield impacts of reduced and no-tillage on a range of crops. Yields of winter cereals were ~6% lower on average in the no-till systems. Anecdotally, farmers report lower yields with no-till practices, but they also report much lower costs for labour and fuel, which may compensate for the lower yields: this is a confirmed in general in a review by Kazimierczuk et al. (2023).

While yields may be lower for regenerative farmers (for some crops), there are a variety of ways that farmers can offset these losses in income. Organic farmers have benefited from premium pricing for their products for many years, and some regenerative farmers are also developing markets for their products on the basis that consumers recognise and value the "regenerative" brand. Most prominent of these brands is WildFarmed[101] which contracts farmers to produce grains according to their own regenerative standard that includes reductions in fertiliser and pesticide inputs as well as a preference for genetically diverse seeds and intercropping (living mulches and cereal/legumes) systems.

Regenerative farmers may access alternative income streams from emerging markets in carbon, biodiversity net gain and nutrient neutrality. Local groups like the Green Farm Collective[102] are adding value to their farming system through trading in biodiversity and carbon markets. Regenerate Outcomes[103] works with Understanding

[101] https://wildfarmed.com/

[102] https://www.greenfarmcollective.com/

[103] https://www.regenerateoutcomes.co.uk/

Ag[104] to support their members in the transition to regenerative agriculture and access to income streams for the carbon and biodiversity benefits they deliver.

Defra's Sustainable Farming Incentive also provides financial benefits to farmers adopting a range of practices that are "regenerative" including the use of cover crops and multispecies leys and reductions in pesticide inputs.

Stacking of these various income streams can allow regenerative farmers to build financially viable businesses even if net output in conventional terms (e.g. yields of commodity crops/ha) is lower.

The landscape for funding regenerative agriculture through government and private schemes and premium product markets is rapidly changing. We are not aware of any studies which have objectively assessed the relative benefits of these routes to funding regenerative farming systems within the UK context.

Economic benefits continue to be a key factor influencing practice changes, as Sophie Gregory emphasised at the Future of Farming conference. 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. This is a high-priority area for applied research and knowledge exchange.

6.2 Socioeconomic factors constraining uptake of regen ag/levers for change

There is an extensive body of academic and grey literature that discusses the factors influencing farmer behaviour change and uptake of novel farming practices. The nature of this topic dictates that most of these studies have a specific geographical focus; local cultural and social conditions (e.g. land tenure, education levels, access to financial resources, government policies) are key determinants of farmer behaviour and vary depending on the country and region. For this reason, we have focussed primarily on studies conducted in the UK. Studies with a regenerative/agroecological theme are most relevant, however, studies that consider changes in farmer behaviour linked to other farming systems/practices may also be relevant.

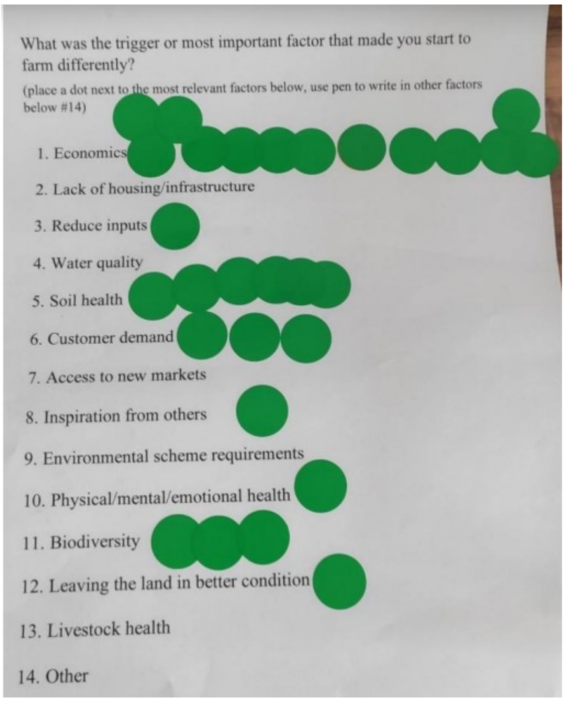
There have been various recent projects which have addressed the question of barriers and enablers to farmer uptake of regenerative and agroecological practices (Magistrali et al. 2022; Hurley et al. 2023). Magistrali et al. (2022) used workshops and surveys to understand how farmers in the north of England viewed regenerative agriculture and what factors determined the uptake of the practice. Farmers in

---

[104] https://understandingag.com/

Cumbria, primarily involved with livestock systems, highlighted economics and soil health as key determinants of their engagement with regen ag. Noting that the economic benefits were largely due to lower costs of production, rather than higher yields or product prices. This resonates with reasons why many farmers take up direct drilling practices on their land; lower fuel and labour costs are an incentive that compensates for the possible reductions in crop yields. The Magistrali study also cited a lack of knowledge as a common barrier identified in workshops and surveys (Figure 12). Many farmers are relying on social media channels (e.g. YouTube) and books (e.g. Gabe Brown's Dirt to Soil, published in 2018, which is hugely influential) for guidance on how to farm regeneratively. With many of this information originating in a different social and environmental context, there is an opportunity for more UK-specific, evidence-based advice on regenerative farming methods. There is also a recognition that even within the UK, appropriate practices will vary depending on the region, so very local, practical advice is needed (Magistrali et al. 2022). The quote from study shown in the box above sums up a common theme relating to access to knowledge and information as a barrier to uptake of regenerative agriculture.

Figure 11 Example from a farmer workshop in Cumbria indicating primary reasons for taking up regenerative agriculture practices (Magistrali et al. 2022)



A quote from farmers interviewed as part of the Magistrali et al (2022) survey of regenerative agriculture in the north of England.

"I'm sure that many farmers know that things are wrong with their farm finances and their farming system … whilst they know change is necessary, they have generally known nothing else than the status quo and so when there is no one there to help them develop a vision for change and show them a way out of the predicament, they revert back to the status quo, because it is all that they know."

While some farmers take up regenerative agriculture practices for economic reasons, others are hesitant because of concerns about financial risks. At the time of the

Magistrali study, there was also uncertainty about future environmental stewardship schemes. However, the rollout of the SFI with various options aligned to regenerative practices has removed some of that uncertainty.

Figure 12 Figure extracted from Magistrali et al. (2022) illustrating barriers to uptake of regenerative agriculture in the north of England

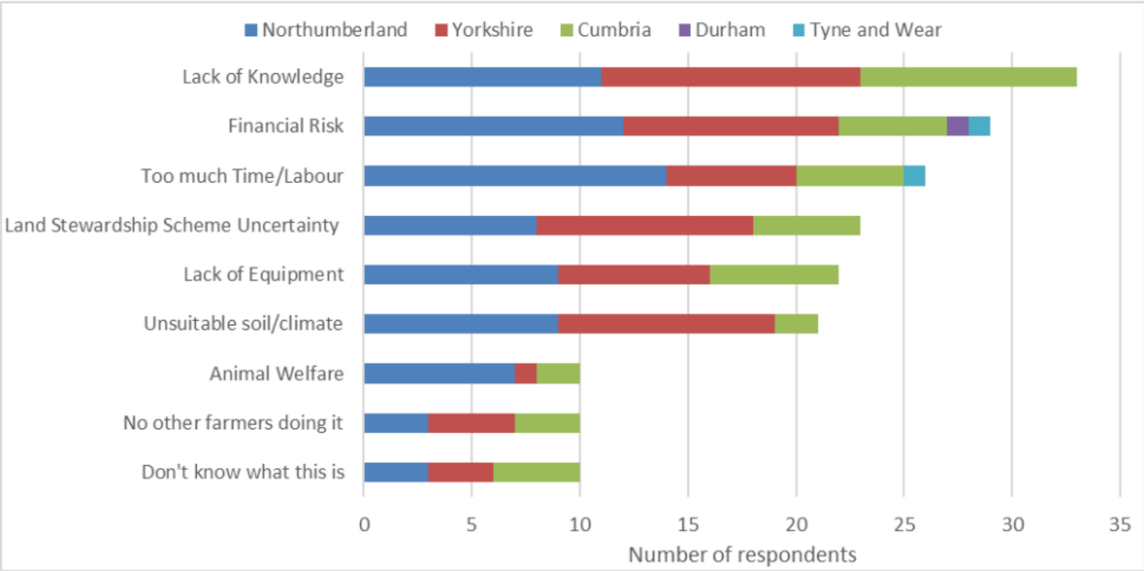
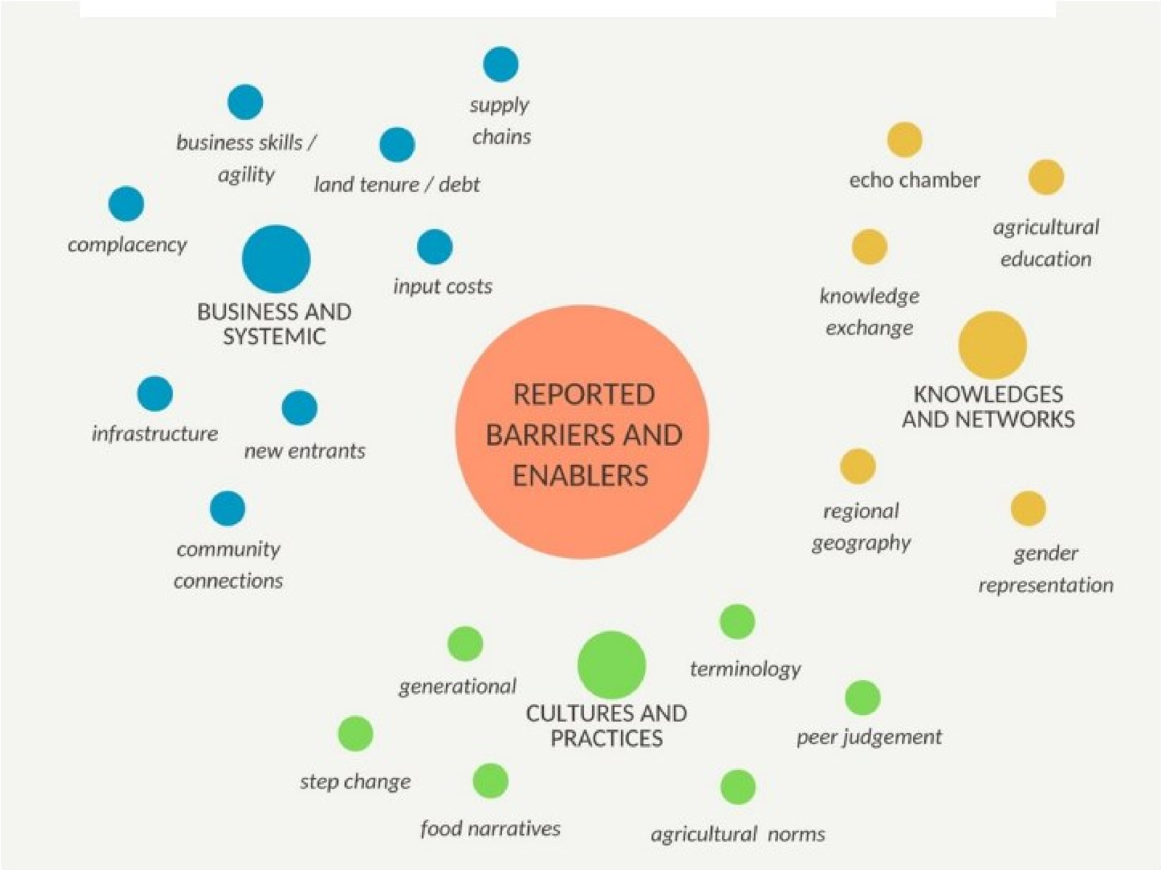


Figure 9 Farmer responses selecting barriers to adoption of regenerative agriculture in the North of England

The study by Hurley et al. (2023) included interviews with a broad range of stakeholders that included farmers, but also researchers, government representatives etc. They highlighted many barriers in common with Magistrali et al, including a lack of perceived financial viability, and limited support for knowledge sharing and networks. But they also reported land tenure constraints, lack of policy support, and cheap food narratives as additional barriers. Figure 13 illustrates these barriers and enablers grouping them under three themes: business and systemic, knowledges and networks, and cultures and practices. A survey by Lozada and Karley (2022) in Scotland echoes many of these themes, particularly emphasising the need for training and advice that takes into account local contexts.

Figure 13 Representation of the barriers and enablers for adoption of agroecological and regenerative farming practices from the study by Hurley et al. (2023)



Studies have already highlighted that there are a range of barriers and constraints to the uptake of regenerative agriculture practices. Information and knowledge are identified as significant, but by no means the only, barriers in most studies. Knowledge exchange (KE) activities that integrate research outcomes with practical guidance are essential (see Challenge 2: Advice and Guidance). This is a high-priority area for policy development action underpinned by social science research.

4 Summary of Key Findings

Table 14 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.

5 Conclusions & Next Steps

This study confirmed many of the same research priorities as identified by the previous reviews mentioned in the introduction (Albanito et al, Burgess et al, AUC review of farmer priorities). But within this project we have gone one step further by conducting a comprehensive assessment of past projects related to the 34 priority topics, as well as reports and peer-reviewed literature. This has helped to pinpoint where the gaps in knowledge lie. In many cases there is already extensive peer-reviewed literature, but a lack of UK context-specific projects and research activities. Farmer-centred approaches to research in real-world conditions will be the best way to address these knowledge gaps. Farmer-participatory approaches will not only address questions around the science and application of regenerative agriculture methods but will also embed the learning within the farming community. Guidance and case studies can be developed directly from these farmer experiences and knowledge transferred in farmer-to-farmer interactions. In all cases, since regenerative agriculture represents a suite of practices that interact with local environments and management contexts, a farming-systems approach will be important to tease out the key factors driving outcomes.

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 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.

Table 14 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. "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. KE=knowledge exchange

		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

Alletto L, Coquet Y, Justes E (2011) Effects of tillage and fallow period management on soil physical behaviour and maize development. Agric Water Manag 102:74–85. https://doi.org/10.1016/j.agwat.2011.10.008

Allison MF, Armstrong MJ, Jaggard KW, Todd AD (1998) Integration of nitrate cover crops into sugarbeet (Beta vulgaris) rotations. I. Management and effectiveness of nitrate cover crops. Journal of Agricultural Science 130:53-60. https://doi.org/10.1017/S0021859697005108

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

Baresel JP, Nichols P, Charrois A, Schmidhalter U (2018) Adaptation of ecotypes and cultivars of subterranean clover (Trifolium subterraneum L.) to German environmental conditions and its suitability as living mulch. Genet Resour Crop Evol 65:2057–2068. https://doi.org/10.1007/s10722-018-0672-z

Barnes AP, Willock J, Hall C, Toma L (2009) Farmer perspectives and practices regarding water pollution control programmes in Scotland. Agric Water Manag 96:1715–1722. https://doi.org/10.1016/j.agwat.2009.07.002

Barraclough PB, Howarth JR, Jones J, et al (2010) Nitrogen efficiency of wheat: Genotypic and environmental variation and prospects for improvement. European Journal of Agronomy 33:1–11. https://doi.org/10.1016/j.eja.2010.01.005

Ben M'Barek S, Karisto P, Abdedayem W, et al (2020) Improved control of septoria tritici blotch in durum wheat using cultivar mixtures. Plant Pathol 69:1655-1665. https://doi.org/10.1111/ppa.13247

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

Bhaduri D, Sihi D, Bhomik A, et al (2022) A review on effective soil health bio-indicators for ecosystem restoration and sustainability. Front Microbiol 13:938481

Bhogal A, White C, Morris N (2020) ADAS Project Report No. 620 Maxi Cover Crop: Maximising the benefits from cover crops through species selection and crop management

Bickler C, Bliss K (2016) Intercropping and Companion Cropping in Arable Systems Innovative Farmers Field Lab 2018-19 report

Bietila E, Silva EM, Pfeiffer AC, Colquhoun JB (2017) Fall-sown cover crops as mulches for weed suppression in organic small-scale diversified vegetable production. Renewable Agriculture and Food Systems 32:349-357. https://doi.org/10.1017/S1742170516000259

Blanco-Canqui H, Wortmann CS (2020) Does occasional tillage undo the ecosystem services gained with no-till? A review. Soil Tillage Res 198:104534. https://doi.org/10.1016/j.still.2019.104534

Bloomer DJ, Harrington KC, Ghanizadeh H, James TK (2024a) Robots and shocks: emerging non-herbicide weed control options for vegetable and arable cropping. New Zealand Journal of Agricultural Research 67:81-103

Bloomer DJ, Harrington KC, Ghanizadeh H, James TK (2024b) Pots to Plots: Microshock Weed Control Is an Effective and Energy Efficient Option in the Field. Sustainability 16:4324. https://doi.org/10.3390/su16114324

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

Brunyee J, Semple D (2021) The Great Project Paper One: Regenerative Agriculture: Context, Definitions and Drivers of Change

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

Bürki H-M, Lawrie J, Greaves MP, et al (2001) Biocontrol of Amaranthus spp. in Europe: state of the art. BioControl 46:197-210

Carena MJ, Yang J, Caffarel JC, et al (2009) Do different production environments justify separate maize breeding programs? Euphytica 169:141-150

Chee-Sanford JC (2008) Weed seeds as nutritional resources for soil Ascomycota and characterization of specific associations between plant and fungal species. Biol Fertil Soils 44:763-771. https://doi.org/10.1007/s00374-007-0259-x

Cheng L, DiTommaso A, Kao-Kniffin J (2022) Opportunities for Microbiome Suppression of Weeds Using Regenerative Agricultural Technologies. Frontiers in Soil Science 2:838595. https://doi.org/10.3389/fsoil.2022.838595

Christy I, Moore A, Myrold D, Kleber M (2023) A mechanistic inquiry into the applicability of permanganate oxidizable carbon as a soil health indicator. Soil Science Society of America Journal 87:1083-1095. https://doi.org/10.1002/saj2.20569

Ciaccia C, Canali S, Campanelli G, et al (2016) Effect of roller-crimper technology on weed management in organic zucchini production in a Mediterranean climate zone. Renewable Agriculture and Food Systems 31:111-121. https://doi.org/10.1017/S1742170515000046

Clements B, Donaldson G (1997) Clover and cereals: low input bi-cropping. Farming and Conservation 3:12-14

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

Cooledge EC, Sturrock CJ, Atkinson BS, et al (2024) Herbal leys have no effect on soil porosity, earthworm abundance, and microbial community composition compared to a grass-clover ley in a sheep grazed grassland after 2-years. Agric Ecosyst Environ 365:108928. https://doi.org/10.1016/j.agee.2024.108928

Cooper J, Baranski M, Stewart G, et al (2016) Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. Agron Sustain Dev 36:22. https://doi.org/10.1007/s13593-016-0354-1

Costanzo A, Bàrberi P (2016) Field scale functional agrobiodiversity in organic wheat: Effects on weed reduction, disease susceptibility and yield. European Journal of Agronomy 76:1-16. https://doi.org/10.1016/j.eja.2016.01.012

Cougnon M, Durand JL, Julier B, et al (2022) Using perennial plant varieties for use as living mulch for winter cereals. A review. Agron Sustain Dev 42:110. https://doi.org/10.1007/s13593-022-00844-x

Creissen HE, Jorgensen TH, Brown JKM (2016) Increased yield stability of field-grown winter barley (Hordeum vulgare L.) varietal mixtures through ecological processes. Crop Protection 85:1-8. https://doi.org/10.1016/j.cropro.2016.03.001

Crough K, MacMillan TC, Pressland K (2024) UK farmer & grower research priorities

Curadelli F, Alberto M, Uliarte EM, et al (2023) Meta-Analysis of Yields of Crops Fertilized with Compost Tea and Anaerobic Digestate. Sustainability 15:1357. https://doi.org/10.3390/su15021357

Dangi SR, Allen BL, Jabro JD, et al (2024) The Effect of Alternative Dryland Crops on Soil Microbial Communities. Soil Syst 8:4. https://doi.org/10.3390/soilsystems8010004

Debaeke P, Perronne R, Colbach N, et al (2024) Non-chemical weed management: Which crop functions and traits to improve through breeding? Crop Protection 179:106631. https://doi.org/10.1016/j.cropro.2024.106631

Díaz de Otálora X, Epelde L, Arranz J, et al (2021) Regenerative rotational grazing management of dairy sheep increases springtime grass production and topsoil carbon storage. Ecol Indic 125:107484. https://doi.org/10.1016/j.ecolind.2021.107484

Doheny-Adams T, Lilley CJ, Barker A, et al (2018) Constant Isothiocyanate-Release Potentials across Biofumigant Seeding Rates. J Agric Food Chem 66:5108-5116. https://doi.org/10.1021/acs.jafc.7b04610

Döring TF, Annicchiarico P, Clarke S, et al (2015) Comparative analysis of performance and stability among composite cross populations, variety mixtures and pure lines of winter wheat in organic and conventional cropping systems. Field Crops Res 183:235-245. https://doi.org/10.1016/j.fcr.2015.08.009

Döring TF, Knapp S, Kovacs G, et al (2011) Evolutionary plant breeding in cereals-into a new era. Sustainability 3:1944-1971. https://doi.org/10.3390/su3101944

Downie RC, Lin M, Corsi B, et al (2021) Septoria nodorum blotch of wheat: Disease management and resistance breeding in the face of shifting disease dynamics and a changing environment. Phytopathology 111:906-920

Dussart F, Fernández-Huartes M, Watson C, et al (2023) Assessing soil ecosystem health-evaluating more detailed biological community measures and DNA-based approaches Project Report No. 91140002-06

Dzvene AR, Tesfuhuney WA, Walker S, Ceronio G (2023) Management of Cover Crop Intercropping for Live Mulch on Plant Productivity and Growth Resources: A Review. Air, Soil and Water Research 16:1-12. https://doi.org/10.1177/11786221231180079

Elphinstone J, Griffiths B, Goddard M, Stockdale E (2018) Soil Biology and Soil Health Partnership Project 3: Molecular approaches for routine soil-borne disease and soil health assessment-establishing the scope

Elrick W, Luke H, Stimpson K (2022) Exploring opportunities and constraints of a certification scheme for regenerative agricultural practice. Agroecology and Sustainable Food Systems 46:1527-1549. https://doi.org/10.1080/21683565.2022.2121950

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

Esperschütz J, Gattinger A, Mäder P, et al (2007) Response of soil microbial biomass and community structures to conventional and organic farming systems under identical crop rotations. FEMS Microbiol Ecol 61:26-37. https://doi.org/10.1111/j.1574-6941.2007.00318.x

Fierer N, Wood SA, Bueno de Mesquita CP (2021) How microbes can, and cannot, be used to assess soil health. Soil Biol Biochem 153:108111. https://doi.org/10.1016/j.soilbio.2020.108111

Fioratti Junod M, Reid B, Sims I, Miller AJ (2024) Cover crops in cereal rotations: A quantitative review. Soil Tillage Res 238:105997. https://doi.org/10.1016/j.still.2023.105997

Fließbach A, Oberholzer HR, Gunst L, Mäder P (2007) Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agric Ecosyst Environ 118:273-284. https://doi.org/10.1016/j.agee.2006.05.022

Fontaine S, Abbadie L, Aubert M, et al (2024) Plant-soil synchrony in nutrient cycles: Learning from ecosystems to design sustainable agrosystems. Glob Chang Biol 30:e17034. https://doi.org/10.1111/gcb.17034

Fradgley N, Evans G, Biernaskie JM, et al (2020) Effects of breeding history and crop management on the root architecture of wheat. Plant Soil 452:587-600. https://doi.org/10.1007/s11104-020-04585-2

Gabbrielli M, Corti M, Perfetto M, et al (2022a) Satellite-Based Frost Damage Detection in Support of Winter Cover Crops Management: A Case Study on White Mustard. Agronomy 12:. https://doi.org/10.3390/agronomy12092025

Gabbrielli M, Perego A, Acutis M, Bechini L (2022b) A review of crop frost damage models and their potential application to cover crops. Italian Journal of Agronomy 17:2046. https://doi.org/10.4081/ija.2022.2046

Gao J, Zhang F (2023) Influence of Companion Planting on Microbial Compositions and Their Symbiotic Network in Pepper Continuous Cropping Soil. J Microbiol Biotechnol 33:760-770. https://doi.org/10.4014/jmb.2211.11032

Gattinger A, Muller A, Haeni M, et al (2012) Enhanced top soil carbon stocks under organic farming. Proc Natl Acad Sci U S A 109:18226-18231. https://doi.org/10.1073/pnas.1209429109

Gómez R, Liebman M, Munkvold G (2014) Weed seed decay in conventional and diversified cropping systems. Weed Res 54:13-25. https://doi.org/10.1111/wre.12052

Gruber S, Pekrun C, Möhring J, Claupein W (2012) Long-term yield and weed response to conservation and stubble tillage in SW Germany. Soil Tillage Res 121:49-56. https://doi.org/10.1016/j.still.2012.01.015

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

Hawkesford MJ, Riche AB (2020) Impacts of G x E x M on Nitrogen Use Efficiency in Wheat and Future Prospects. Front Plant Sci 11:1157. https://doi.org/10.3389/fpls.2020.01157

Herremans S, Regibeau S, Huyghebaert B (2021) Impacts of catch crops grazed by sheep: a review. The French journal on grasslands and forages 248:21-28

Herrera JM, Verhulst N, Trethowan RM, et al (2013) Insights into genotype × tillage interaction effects on the grain yield of wheat and maize. Crop Sci 53:1845-1859

Heuchan SM, Wagner-Riddle C, Baral KR, et al (2023) Cover crops increase belowground N retention substantially in corn cropping systems: Results from a 15N residue swapping experiment. Plant Soil. https://doi.org/10.1007/s11104-023-06196-z

Hooks CRR, Johnson MW (2003) Impact of agricultural diversification on the insect community of cruciferous crops. Crop Protection 22:223-238

Howard A (2016) The potential for companion cropping and intercropping on UK arable farms (A Nuffield Farming Scholarships Trust Report)

Hurley PD, Rose DC, Burgess PJ, Staley JT (2023) Barriers and enablers to uptake of agroecological and regenerative practices, and stakeholder views towards 'living labs'

Hussain MI, Araniti F, Schulz M, et al (2022) Benzoxazinoids in wheat allelopathy - From discovery to application for sustainable weed management. Environ Exp Bot 202:104997. https://doi.org/10.1016/j.envexpbot.2022.104997

Jani AD, Grossman J, Smyth TJ, Hu S (2016) Winter legume cover-crop root decomposition and N release dynamics under disking and roller-crimping termination approaches. Renewable Agriculture and Food Systems 31:214-229. https://doi.org/10.1017/S1742170515000113

Jayasinghe SL, Thomas DT, Anderson JP, et al (2023) Global Application of Regenerative Agriculture: A Review of Definitions and Assessment Approaches. Sustainability 15:15941. https://doi.org/10.3390/su152215941

Joergensen RG, Mäder P, Fließbach A (2010) Long-term effects of organic farming on fungal and bacterial residues in relation to microbial energy metabolism. Biol Fertil Soils 46:303-307. https://doi.org/10.1007/s00374-009-0433-4

Jones L (1992) Preliminary trials using a white clover (Trifolium repens L.) understorey to supply nitrogen requirements of a cereal crop. Grass and Forage Science 47:366-374

Jones L, Clements RO (1993) Development of a low input system for growing wheat (Triticum vulgare) in a permanent understorey of white clover (Trifolium repens). Annals of Applied Biology 123:109-119

Joos L, De Tender C, Holderbeke A, et al (2023) Exploring the microbial response as a potential bio-indicator for soil health: Insights from a controlled incubator experiment. Agric Ecosyst Environ 356:108634. https://doi.org/10.1016/j.agee.2023.108634

Jordon MW, Buffet JC, Dungait JAJ, et al (2024) A restatement of the natural science evidence base concerning grassland management, grazing livestock and soil carbon storage. Proceedings of the Royal Society B: Biological Sciences 291:20232669. https://doi.org/10.1098/rspb.2023.2669

Jordon MW, Winter DM, Petrokofsky G (2023) Advantages, disadvantages, and reasons for non-adoption of rotational grazing, herbal leys, trees on farms and ley-arable rotations on English livestock farms. Agroecology and Sustainable Food Systems 47:330–354. https://doi.org/10.1080/21683565.2022.2146253

Joshi AK, Chand R, Arun B, et al (2007) Breeding crops for reduced-tillage management in the intensive, rice-wheat systems of South Asia. Euphytica 153:135–151. https://doi.org/10.1007/s10681-006-9249-6

Kao-Kniffin J, Carver SM, DiTommaso A (2013) Advancing Weed Management Strategies Using Metagenomic Techniques. Weed Sci 61:171–184. https://doi.org/10.1614/ws-d-12-00114.1

Kareem SHS, Hawkesford MJ, DeSilva J, et al (2022) Root architecture and leaf photosynthesis traits and associations with nitrogen-use efficiency in landrace-derived lines in wheat. European Journal of Agronomy 140:126603. https://doi.org/10.1016/j.eja.2022.126603

Kaufmann S, Hruschka N, Vogl CR (2023) Participatory Guarantee Systems, a more inclusive organic certification alternative? Unboxing certification costs and farm inspections in PGS based on a case study approach. Front Sustain Food Syst 7:1176057. https://doi.org/10.3389/fsufs.2023.1176057

Kavamura VN, Robinson RJ, Hughes D, et al (2020) Wheat dwarfing influences selection of the rhizosphere microbiome. Sci Rep 10:1452. https://doi.org/10.1038/s41598-020-58402-y

Kazimierczuk K, Barrows SE, Olarte M V., Qafoku NP (2023) Decarbonization of Agriculture: The Greenhouse Gas Impacts and Economics of Existing and Emerging Climate-Smart Practices. ACS Engineering Au 3:426–442. https://doi.org/10.1021/acsengineeringau.3c00031

King J, Gay A, Sylvester-Bradley R, et al (2003) Modelling cereal root systems for water and nitrogen capture: Towards an economic optimum. Ann Bot 91:383-390. https://doi.org/10.1093/aob/mcg033

Kinnunen-Grubb M, Sapkota R, Vignola M, et al (2020) Breeding selection imposed a differential selective pressure on the wheat root-associated microbiome. FEMS Microbiol Ecol 96:fiaa196

Krause H-M, Stehle B, Mayer J, et al (2022) Biological soil quality and soil organic carbon change in biodynamic, organic, and conventional farming systems after 42 years. Agron Sustain Dev 42:117. https://doi.org/10.1007/s13593-022-00843-y

Księżak J, Staniak M, Stalenga J (2023) Restoring the Importance of Cereal-Grain Legume Mixtures in Low-Input Farming Systems. Agriculture 13:341. https://doi.org/10.3390/agriculture13020341

Kunz C, Sturm DJ, Peteinatos GG, Gerhards R (2016) Unkrautunterdrückung durch Untersaaten in Zuckerrüben. Gesunde Pflanzen 68:145-154. https://doi.org/10.1007/s10343-016-0370-8

Landers JN, de Freitas PL, de Oliveira MC, et al (2021) Next steps for conservation agriculture. Agronomy 11:2496. https://doi.org/10.3390/agronomy11122496

Landschoot S, Zustovi R, Dewitte K, et al (2023) Cereal-legume intercropping: a smart review using topic modelling. Front Plant Sci 14:1228850. https://doi.org/10.3389/fpls.2023.1228850

Lazzaro M, Costanzo A, Bàrberi P (2018) Single vs multiple agroecosystem services provided by common wheat cultivar mixtures: Weed suppression, grain yield and quality. Field Crops Res 221:277-297. https://doi.org/10.1016/j.fcr.2017.10.006

Leigh FJ, Wright TIC, Horsnell RA, et al (2022) Progenitor species hold untapped diversity for potential climate-responsive traits for use in wheat breeding and crop improvement. Heredity (Edinb) 128:291-303. https://doi.org/10.1038/s41437-022-00527-z

Lemke S, Smith N, Thiim C, Stump K (2024) Drivers and barriers to adoption of regenerative agriculture: cases studies on lessons learned from organic. Int J Agric Sustain 22:2324216. https://doi.org/10.1080/14735903.2024.2324216

Lewis RW, Okubara PA, Sullivan TS, et al (2022) Proteome-Wide Response of Dormant Caryopses of the Weed, Avena fatua, after Colonization by a Seed-

Decay Isolate of Fusarium avenaceum. Phytopathology 112:1103-1117. https://doi.org/10.1094/PHYTO-06-21-0234-R

Li X, Storkey J, Mead A, et al (2023) A new Rothamsted long-term field experiment for the twenty-first century: principles and practice. Agron Sustain Dev 43:60. https://doi.org/10.1007/s13593-023-00914-8

Litterick AM, Harrier L, Wallace P, et al (2004) The role of uncomposted materials, composts, manures, and compost extracts in reducing pest and disease incidence and severity in sustainable temperate agricultural and horticultural crop production - A review. CRC Crit Rev Plant Sci 23:453–479

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

Lord JS, Lazzeri L, Atkinson HJ, Urwin PE (2011) Biofumigation for control of pale potato cyst nematodes: Activity of brassica leaf extracts and green manures on globodera pallida in vitro and in soil. J Agric Food Chem 59:7882–7890. https://doi.org/10.1021/jf200925k

Lozada LM, Karley A (2022) The Adoption of Agroecological Principles in Scottish Farming and their Contribution towards Agricultural Sustainability and Resilience

Lynch JP (2013) Steep, cheap and deep: An ideotype to optimize water and N acquisition by maize root systems. Ann Bot 112:347–357

Machmuller MB, Kramer MG, Cyle TK, et al (2015) Emerging land use practices rapidly increase soil organic matter. Nat Commun 6:6995. https://doi.org/10.1038/ncomms7995

Magistrali A, Cooper J, Franks J, et al (2022) Identifying and implementing regenerative agriculture practices in challenging environments: experiences of farmers in the north of England. Newcastle Upon Tyne

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

Marks BA (2020) (Carbon) Farming Our Way Out of Climate Change. Denver Law Review 97:497-556

Martínez I, Chervet A, Weisskopf P, et al (2016) Two decades of no-till in the Oberacker long-term field experiment: Part I. Crop yield, soil organic carbon and nutrient distribution in the soil profile. Soil Tillage Res 163:141-151. https://doi.org/10.1016/j.still.2016.05.021

Masters N (2019) For the love of soil: Strategies to regenerate our food production systems. Printable Reality

Mattila TJ (2024) Redox potential as a soil health indicator - how does it compare to microbial activity and soil structure? Plant Soil 494:617-625. https://doi.org/10.1007/s11104-023-06305-y

Mayer M, Krause H-M, Fliessbach A, et al (2022) Fertilizer quality and labile soil organic matter fractions are vital for organic carbon sequestration in temperate arable soils within a long-term trial in Switzerland. Geoderma 426:116080. https://doi.org/10.1016/j.geoderma.2022.116080

McDaniel MD, Bird JA, Pett-Ridge J, et al (2023) Diversifying and perennializing plants in agroecosystems alters retention of new C and N from crop residues. Ecological Applications 33:e2784. https://doi.org/10.1002/eap.2784

McGechan MB, Lewis DR, Vinten AJA (2008) A river water pollution model for assessment of best management practices for livestock farming. Biosyst Eng 99:292-303. https://doi.org/10.1016/j.biosystemseng.2007.10.010

McKenna P, Cannon N, Conway J, Dooley J (2018) The use of red clover (Trifolium pratense) in soil fertility-building: A Review. Field Crops Res 221:38-49

Mofikoya AO, Bui TNT, Kivimäenpää M, et al (2019) Foliar behaviour of biogenic semi-volatiles: potential applications in sustainable pest management. Arthropod Plant Interact 13:193-212

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

Montoya JE, Arnold MA, Rangel J, et al (2020) Pollinator-attracting companion plantings increase crop yield of cucumbers and habanero peppers. HortScience 55:164-169. https://doi.org/10.21273/HORTSCI14468-19

Mooney S, Carter A, Hynds P, et al (2024) On-farm pro-environmental diversification: A qualitative analysis of narrative interviews with Western-European farmers. Agroecology and Sustainable Food Systems 48:93-123. https://doi.org/10.1080/21683565.2023.2269380

Moore VM, Maul JE, Wilson D, et al (2020) Registration of ‘Purple Bounty’ and ‘Purple Prosperity’ hairy vetch. J Plant Regist 14:340-346. https://doi.org/10.1002/plr2.20044

Mooshammer M, Grandy AS, Calderón F, et al (2022) Microbial feedbacks on soil organic matter dynamics underlying the legacy effect of diversified cropping systems. Soil Biol Biochem 167:108584. https://doi.org/10.1016/j.soilbio.2022.108584

Mosier S, Apfelbaum S, Byck P, et al (2021) Adaptive multi-paddock grazing enhances soil carbon and nitrogen stocks and stabilization through mineral association in southeastern U.S. grazing lands. J Environ Manage 288:112409. https://doi.org/10.1016/j.jenvman.2021.112409

Mouratiadou I, Wezel A, Kamilia K, et al (2024) The socio-economic performance of agroecology. A review. Agron Sustain Dev 44:19. https://doi.org/10.1007/s13593-024-00945-9

Newton P, Civita N, Frankel-Goldwater L, et al (2020) What Is Regenerative Agriculture? A Review of Scholar and Practitioner Definitions Based on Processes and Outcomes. Front Sustain Food Syst 4:577723. https://doi.org/10.3389/fsufs.2020.577723

Nguyen DB, Rose MT, Rose TJ, et al (2016) Impact of glyphosate on soil microbial biomass and respiration: A meta-analysis. Soil Biol Biochem 92:50-57. https://doi.org/10.1016/j.soilbio.2015.09.014

NIAB-TAG (2016) Cover Crops A practical guide to soil and system improvement 2016/17

Nikolić N, Squartini A, Concheri G, et al (2020) Weed seed decay in no-till field and planted riparian buffer zone. Plants 9:293. https://doi.org/10.3390/plants9030293

Ober ES, Alahmad S, Cockram J, et al (2021) Wheat root systems as a breeding target for climate resilience. Theoretical and Applied Genetics 134:1645-1662

Ogle SM, Swan A, Paustian K (2012) No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agric Ecosyst Environ 149:37–49. https://doi.org/10.1016/j.agee.2011.12.010

O'Neill B, Ramos-Abensur V (2022) A review of the state of knowledge and use of liquid ferments and biol in the Andes

Orr CH, James A, Leifert C, et al (2011) Diversity and activity of free-living nitrogen-fixing bacteria and total bacteria in organic and conventionally managed soils. Appl Environ Microbiol 77:911-919. https://doi.org/10.1128/AEM.01250-10

Orr CH, Leifert C, Cummings SP, Cooper JM (2012) Impacts of Organic and Conventional Crop Management on Diversity and Activity of Free-Living Nitrogen Fixing Bacteria and Total Bacteria Are Subsidiary to Temporal Effects. PLoS One 7:e52891. https://doi.org/10.1371/journal.pone.0052891

Page C, Witt B (2022) A Leap of Faith: Regenerative Agriculture as a Contested Worldview Rather Than as a Practice Change Issue. Sustainability 14:14803. https://doi.org/10.3390/su142214803

Panwar L, Devi S, Singh Y (2021) Insect pest management in vegetable crops through trap cropping: Review. Indian Journal of Agricultural Sciences 91:1433-1437

Peixoto DS, Silva L de CM da, Melo LBB de, et al (2020) Occasional tillage in no-tillage systems: A global meta-analysis. Science of the Total Environment 745:104887. https://doi.org/10.1016/j.scitotenv.2020.140887

Phillips SL, Wolfe MS (2005) Evolutionary plant breeding for low input systems. Journal of Agricultural Science 143:245-254

Pittelkow CM, Liang X, Linquist BA, et al (2015) Productivity limits and potentials of the principles of conservation agriculture. Nature 517:365-368. https://doi.org/10.1038/nature13809

Pollard AT (2018) Seeds vs fungi: An enzymatic battle in the soil seedbank. Seed Sci Res 28:197-214. https://doi.org/10.1017/S0960258518000181

Ponisio LC, M'gonigle LK, Mace KC, et al (2015) Diversification practices reduce organic to conventional yield gap. Proceedings of the Royal Society B: Biological Sciences 282:20141396. https://doi.org/10.1098/rspb.2014.1396

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

Powlson DS, Stirling CM, Jat ML, et al (2014) Limited potential of no-till agriculture for climate change mitigation. Nat Clim Chang 4:678-683

Price AJ, Duzy L, Mc Elroy JS, Li S (2019) Evaluation of organic spring cover crop termination practices to enhance rolling/crimping. Agronomy 9:519. https://doi.org/10.3390/agronomy9090519

Pun I, Galdos M V., Chapman PJ, et al (2024) Measuring and modelling the impact of outdoor pigs on soil carbon and nutrient dynamics under a changing climate and different management scenarios. Soil Use Manag 40:e13029. https://doi.org/10.1111/sum.13029

Qin R, Noulas C, Herrera JM (2018) Morphology and distribution of wheat and maize roots as affected by tillage systems and soil physical parameters in temperate climates: an overview. Arch Agron Soil Sci 64:747-762

Rakotomalala AANA, Ficiciyan AM, Tscharntke T (2023) Intercropping enhances beneficial arthropods and controls pests: A systematic review and meta-analysis. Agric Ecosyst Environ 356:108617. https://doi.org/10.1016/j.agee.2023.108617

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

Rebong D, Henriquez Inoa S, Moore VM, et al (2024) Breeding allelopathy in cereal rye for weed suppression. Weed Sci 72:30-40

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

Reiss A, Fomsgaard I, Mathiassen SK, et al (2018) Weed suppression by winter cereals: relative contribution of competition for resources and allelopathy. Chemoecology 28:109-121

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

Reynolds M, Atkin OK, Bennett M, et al (2021) Addressing Research Bottlenecks to Crop Productivity. Trends Plant Sci 26:607–630

Sands B, Machado MR, White A, et al (2023) Moving towards an anti-colonial definition for regenerative agriculture. Agric Human Values 40:1697–1716. https://doi.org/10.1007/s10460-023-10429-3

Sarkar SC, Wang E, Wu S, Lei Z (2018) Application of trap cropping as companion plants for the management of agricultural pests: A review. Insects 9:128

Schmidt O, Curry JP, Hackett RA, et al (2001) Earthworm communities in conventional wheat monocropping and low-input wheat-clover intercropping systems. Annals of Applied Biology 138:377–388. https://doi.org/10.1111/j.1744-7348.2001.tb00123.x

Schöb C, Engbersen N, López-Angulo J, et al (2023) Crop Diversity Experiment: towards a mechanistic understanding of the benefits of species diversity in annual crop systems. Journal of Plant Ecology 16:rtad016. https://doi.org/10.1093/jpe/rtad016

Seimandi-Corda G, Winkler J, Jenkins T, et al (2024) Companion plants and straw mulch reduce cabbage stem flea beetle (Psylliodes chrysocephala) damage on oilseed rape. Pest Manag Sci 80:2333–2341. https://doi.org/10.1002/ps.7641

Seufert V, Ramankutty N, Foley JA (2012) Comparing the yields of organic and conventional agriculture. Nature 485:229–232

Sharma A, Soni R, Soni SK (2024) From waste to wealth: exploring modern composting innovations and compost valorization. J Mater Cycles Waste Manag 26:20–48

Shawver CJ, Ippolito JA, Brummer JE, et al (2021) Soil health changes following transition from an annual cropping to perennial management-intensive grazing agroecosystem. Agrosystems, Geosciences and Environment 4:e20181. https://doi.org/10.1002/agg2.20181

Sherwood S, Uphoff N (2000) Soil health: research, practice and policy for a more regenerative agriculture. Applied Soil Ecology 15:85-97

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

Soil Association (2016) The impact of glyphosate on soil health. The evidence to date

Storer K, Berdini D (2022) Defra EEF Review - WP1 Final Report: Evidence needs to enable effective usage of plant biostimulants

Storer K, Kendall S, White C, et al (2016) A review of the function, efficacy and value of biostimulant products available for UK Cereals & Oilseed

Storr T, Simmons RW, Hannam JA (2021) Using frost-sensitive cover crops for timely nitrogen mineralization and soil moisture management. Soil Use Manag 37:427-435. https://doi.org/10.1111/sum.12619

Sumption P (2023) The Organic Vegetable Grower A practical guide to growing for the market, First. The Crowood Press, Ltd., Marlborough, Wiltshire

Swanston JS, Newton AC (2005) Mixtures of UK wheat as an efficient and environmentally friendly source for bioethanol. J Ind Ecol 9:109-126

Swanston JS, Newton AC, Hoad SP, Spoor W (2006) Variation across environments in patterns of water uptake and endosperm modification in barley varieties and variety mixtures. J Sci Food Agric 86:826-833. https://doi.org/10.1002/jsfa.2421

Sylvester-Bradley R, Kindred DR (2009) Analysing nitrogen responses of cereals to prioritize routes to the improvement of nitrogen use efficiency. J Exp Bot 60:1939-1951

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

Teague WR, Dowhower SL, Baker SA, et al (2011) Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agric Ecosyst Environ 141:310-322. https://doi.org/10.1016/j.agee.2011.03.009

Thirkell TJ, Grimmer M, James L, et al (2022) Variation in mycorrhizal growth response among a spring wheat mapping population shows potential to breed for symbiotic benefit. Food Energy Secur 11:e370. https://doi.org/10.1002/fes3.370

Trickett T, Warner DJ (2022) Earthworm Abundance Increased by Mob-Grazing Zero-Tilled Arable Land in South-East England. Earth 3:895-906. https://doi.org/10.3390/earth3030052

Trimarco T, Brummer JE, Buchanan C, Ippolito JA (2023) Tracking Soil Health Changes in a Management-Intensive Grazing Agroecosystem. Soil Syst 7:94. https://doi.org/10.3390/soilsystems7040094

Van den Putte A, Govers G, Diels J, et al (2010) Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture. European Journal of Agronomy 33:231-241. https://doi.org/10.1016/j.eja.2010.05.008

Van Der Bom FJT, Williams A, Bell MJ (2020) Root architecture for improved resource capture: Trade-offs in complex environments. J Exp Bot 71:5752-5763

Vann RA, Reberg-Horton SC, Castillo MS, et al (2019) Winter pea, crimson clover, and hairy vetch planted in mixture with small grains in the southeast United States. Agron J 111:805-815. https://doi.org/10.2134/agronj2018.03.0202

Venter ZS, Jacobs K, Hawkins HJ (2016) The impact of crop rotation on soil microbial diversity: A meta-analysis. Pedobiologia (Jena) 59:215-223. https://doi.org/10.1016/j.pedobi.2016.04.001

Wacławowicz R, Giemza M, Pytlarz E, Wenda-Piesik A (2023) The Impact of Cultivation Systems on Weed Suppression and the Canopy Architecture of Spring Barley. Agriculture 13:1747. https://doi.org/10.3390/agriculture13091747

Wayman S, Cogger C, Benedict C, et al (2015) The influence of cover crop variety, termination timing and termination method on mulch, weed cover and soil nitrate in reduced-tillage organic systems. Renewable Agriculture and Food Systems 30:450–460. https://doi.org/10.1017/S1742170514000246

Weedon OD, Brumlop S, Haak A, et al (2023) High Buffering Potential of Winter Wheat Composite Cross Populations to Rapidly Changing Environmental Conditions. Agronomy 13:1662. https://doi.org/10.3390/agronomy13061662

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

White CA, Holmes HF, Morris NL, Stobart RM (2016) AHDB Research Review No. 90 A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species

Wolfe MS, Ceccarelli S (2020) The increased use of diversity in cereal cropping requires more descriptive precision. J Sci Food Agric 100:4119–4123. https://doi.org/10.1002/jsfa.9906

Wood C, Kenyon DM, Cooper JM (2017) Allyl isothiocyanate shows promise as a naturally produced suppressant of the potato cyst nematode, globodera pallida, in biofumigation systems. Nematology 19:389–402

Woolford AR, Jarvis PE (2017) Cover, Catch and Companion Crops Benefits, Challenges and Economics for UK Growers

Worthington M, Reberg-Horton C (2013) Breeding Cereal Crops for Enhanced Weed Suppression: Optimizing Allelopathy and Competitive Ability. J Chem Ecol 39:213–231. https://doi.org/10.1007/s10886-013-0247-6

Wortman SE, Francis CA, Bernards ML, et al (2012) Optimizing cover crop benefits with diverse mixtures and an alternative termination method. Agron J 104:1425-1435. https://doi.org/10.2134/agronj2012.0185

Zhang WP, Surigaoge S, Yang H, et al (2024) Diversified cropping systems with complementary root growth strategies improve crop adaptation to and remediation of hostile soils. Plant Soil. https://doi.org/10.1007/s11104-023-06464-y

Zhu X, Xie H, Masters MD, et al (2023) Microorganisms, their residues, and soil carbon storage under a continuous maize cropping system with eight years of variable residue retention. Applied Soil Ecology 187:104846. https://doi.org/10.1016/j.apsoil.2023.104846

Zustovi R, Landschoot S, Dewitte K, et al (2024) Intercropping indices evaluation on grain legume-small grain cereals mixture: a critical meta-analysis review. Agron Sustain Dev 44:5. https://doi.org/10.1007/s13593-023-00934-4

Annex 1 Summary of Workshop Outcomes - Prioritisation of research needs for regenerative agriculture systems in the UK

The workshop was held online on the 7 February 2024, hosted by Julia Cooper (Organic Research Centre), Elizabeth Stockdale (NIAB) and Belinda Clarke (Agri-TechE).

Nineteen people attended; they identified themselves as indicated in Table 15. Almost all were scientists, with only one farmer participating, although farmers had been included on the invitation list. Participants completed a survey during the workshop where they were asked to prioritise knowledge gaps from the list in Table . A few gaps were identified to be of critical/high importance.

Table 15 Categories of individuals attending the workshop

Stakeholder Categories	
Agronomist/advisor	1
Farmer	1
Plant scientist	5
Social scientist	2
Policy	1
Soil scientist	5
Executive role	3
Ecologist	1
Total	**19**

- **Understanding of the impact (and the factors affecting it) of regenerative agriculture systems on farm livelihoods** was considered critical or high by all respondents to the survey. Most respondents selected applied or KE research as the best approach. Text comments confirmed this importance, e.g. "If there is evidence that farm livelihoods (incomes) are improved through regen ag, then more farmers will take it up. So it is really important."
- **Better understanding of the main socio-economic factors constraining uptake of regenerative agriculture** was also mainly scored as critical or high in importance, although a few respondents disagreed, scoring it as low importance. Applied or KE approaches were generally favoured for this gap with socio-economic approaches identified in the text comments, e.g. "Multidisciplinary research platforms including farmers, social and "hard" researchers", "Qualitative research that leads to policy recommendations", "Social science research - eg. surveys, interviews into socio-economic barriers and drivers influencing the adoption of regen"
- The lack of a **"clear farmland soil carbon code in the UK"** was considered critical by 7 respondents but another 7 thought it was only of normal importance. Further analysis will determine if the soil scientists in the workshop all prioritised this gap! It was seen as a policy gap although a few respondents (5) felt more fundamental/basic research was needed. It was seen as a barrier to regen uptake "Until farmers can be compensated for building carbon in their soils, they won't be keen to adopt regen ag" and some urgency was noted "Quickly (even if just to say that it won't be adopted). Currently the limbo is causing unintended consequences"
- Most of the gaps were scored as of high to normal importance and applied research approaches were most often identified as the best approach.

- Basic/fundamental research was only identified as the best approach for three gaps: **Breeding of crop varieties with enhanced disease & insect tolerance**, **The impact of regenerative agriculture systems on food quality, particularly nutrient density** and **Evidence of the wider and indirect benefits of working with plant populations rather than single crop varieties or varietal blends** (scored slightly lower on the importance of this research).

During the breakout sessions participants highlighted a number of other areas that they felt should have been included in the survey, including:

- Tillage and questions around impacts of no-till versus occasional/strategic tillage
- Agroforestry and other multifunctional land uses
- Several attendees felt that a clear definition of regenerative agriculture is needed
- The impacts of increased herbicide use in regenerative agriculture systems (noting that there has been work done in other parts of the world on this) and/or how to reduce reliance on herbicide in reduced tillage systems
- Work on supporting system change by farmers; understanding antagonism of some farmers and barriers to change
- Need for really long-term studies to understand impacts of regen ag on soils and ecology
- Need for more fundamental science on how soils function
- Root crops/horticultural crops not really covered in the questions
- Payment schemes/incentives to drive system change

There was a general feeling from many of the participants that not all gaps were covered and that a systems approach to research on regen ag is needed. It was also duly noted that the participants were very much skewed towards scientists; another group of stakeholders would have prioritised the gaps differently.

Overall, the workshop provided extremely valuable insights and areas for further discussion and development. These will be pursued through more review of literature and project outputs as well as further targeted interviews with key stakeholders. A more detailed analysis will be presented at the conference in March.

Table 1A List of knowledge gaps included in the workshop survey with preliminary analysis of type of research needed and priority of that research gap. P=policy, KE=knowledge exchange, A=applied, F/B=fundamental/basic, HN=high/normal, NL=normal/low, CH=critical/high

		Type	Priority
1	There are no/few metrics that can be used to define regenerative agriculture systems	P	CH/HN/NL
2	Implementation of regenerative agriculture practices is underpinned by agreed principles, but there is no locally tailored independent information to support a farm implementing regenerative agriculture	KE	HN
3	How to integrate root crops e.g. potatoes, carrots into regenerative rotations	A	HN
4	How to grow intercrops (i.e. two or more crops grown together and both harvested) effectively	A/KE	HN
5	How to grow varietal blends effectively	A	HN
6	How to use companion planting (two crops sown together; only one taken to harvest) effectively	A/KE	HN
7	How to implement living mulch systems (permanent clover understorey in a cash crop) successfully	A	HN
8	How to effectively terminate cover crops without impacts on the following crop	A	HN
9	The best cover crops for colder (e.g. northern) conditions	A	HN
10	Impact of changes in soil biology on weeds, particularly blackgrass	A	HN
11	Effects of cover crops on disease & insect pressure in subsequent /neighbouring crops	A	HN
12	Breeding of crop varieties with enhanced disease & insect tolerance	F/B	HN
13	Variety evaluation with low/no plant protection products and/or reduced N application	A	HN
14	The impact of variety blends on product quality and end-market use	A	HN
15	Variety evaluation that includes a description of rooting traits	A	HN
16	How to enable use of landraces and other heterogenous material (e.g. plant populations).	all	NL
17	Evidence of the wider and indirect benefits of working with plant populations rather than single crop varieties or varietal blends.	B/A	HN/NL
18	Evidence of the impacts of mob grazing on soil and livestock health	A	HN
19	Development of cost-effective soil health indicators addressing soil biological function	all	HN
20	Evidence of the impacts of biostimulants on plant and soil health	A	HN
21	Evidence of the impacts of regenerative agriculture systems on the water cycle (flood risk, drought resilience)	A	HN
22	Evidence to allow options for regenerative agriculture to be assessed in terms of wider impacts (e.g. whole life cycle analysis for input options)	A	HN
23	Evidence of the impacts of integration of legumes throughout the cropping system on N cycling including GHG emissions	A	HN
24	How to design crop rotations to optimise economic and environmental benefits	A/KE	HN
25	The impact of lower input use (N fertiliser and plant protection products) within regenerative agriculture on product quality and end-market use	A	HN
26	Understanding of the impact (and the factors affecting it) of regenerative agriculture systems on farm livelihoods	all	CH
27	The impact of regenerative agriculture systems on food quality, particularly nutrient density	F/B	HN
28	Evidence of the potential benefits and disbenefits of developing a certification scheme for regenerative agriculture	P	HN
29	Development of a clear farmland soil carbon code in the UK	P	CH/HN
30	Better understanding of the main socio-economic factors constraining uptake of regenerative agriculture	all	CH
31	The potential benefits and disbenefits of food manufacturers and retailers championing regenerative agriculture.	all	HN

Annex 2 Summary tables from survey and discussion during the expert's workshop

Table 4A Summary of Regenerative Agriculture Knowledge Gaps - General

Gap/Topic ***Priority:Approach***	**Key Comments - Survey/ChatGPT 40-word summary/*Discussion***
1. Identification/definition of metrics that can be used to define regenerative agriculture systems ***CH/HN/NL:P***	Greenwashing exposure is vital, but consensus on regenerative agriculture's definition precedes metric establishment. Equipment adherence to standards is essential. Define regenerative components and establish accepted metrics. *Some participants felt strongly that regenerative agriculture needs to be defined and codified if we are to do robust research about it. There is a real need for work on a definition: should this be outcomes or practice-based?*
2. Lack of locally tailored independent information to support a farm implementing regenerative agriculture ***HN:KE***	Regenerative agriculture's success is context-specific, requiring local guidance. Define regen ag, establish farmer cooperatives for research, reintroduce experimental farms, and ensure independent extension work and knowledge exchange to avoid biases. *Concerns about misinformation, "especially within the regen ag world…" were raised*

P=policy, KE=knowledge exchange, A=applied, F/B=fundamental/basic, HN=high/normal, NL=normal/low, CH=critical/high

Table 4B Summary of Regenerative Agriculture Knowledge Gaps - Agronomic

Gap/Topic *Priority:Approach*	Key Comments - Survey/ChatGPT 40-word summary/*Discussion*
3. How to integrate root crops e.g. potatoes, carrots into regenerative rotations *HN:A*	Research on root crop integration in regenerative systems is crucial for UK soil health. Field trials identifying optimal frequency are essential. Incentivize funding from processors and retailers for farmer cooperatives. Transfer arable rotation principles for regeneration.
4. How to grow intercrops (i.e. two or more crops grown together and both harvested) effectively *HN:A/KE*	Intercropping is vital for diversified regenerative systems. Utilize regional demos, Ben Adams' work, and global practices. Exchange knowledge and conduct field trials with farmers for effective implementation.
5. How to use companion planting (two crops sown together; only one taken to harvest) effectively *HN:A/KE*	Companion planting, while interesting in regenerative agriculture, isn't essential. Utilize farmer experiences, Ben Adams' DEFRA-funded work, and engage with agricultural engineers. Apply agroecological research and disseminate practical guides through farm clusters.
6. How to implement living mulch systems (permanent clover understorey in a cash crop) successfully *HN:A*	Challenging to implement, yet nonessential for regenerative agriculture adoption. Share farmer experiences, support field trials, and conduct diverse research to enhance understanding across various rotations and regions.
7. How to effectively terminate cover crops without impacts on the following crop *HN:A*	Engage researchers with diverse termination approaches. Address prevalent questions with extensive research and government intervention. Conduct observational research, tramline trials, and mechanical method trials to assess cover crop adoption challenges. Utilize farmer clusters for knowledge exchange and applied research.
8. The best cover crops for local environments, e.g. cooler northern climates, hotter southern climates, heavy soils etc. *HN:A*	Cover crops are vital to regenerative agriculture, yet their suitability across climates is unclear. Regional demos, farmer groups, and knowledge exchange are crucial. Independent advice and variety trials are needed to identify well-adapted cover crops, addressing farmers' concerns and knowledge gaps.
9. Effects of cover crops on disease & insect pressure in subsequent /neighbouring crops *HN:A*	Understanding how cover crops impact pests and beneficials requires field ecology comprehension. Utilize demonstration farms, knowledge exchange events, and long-term tramline trials in various contexts. Assess cover crops' effects on pest and disease dynamics with adjacent farmer crops for practical insights.
10. Evidence of the impacts of biostimulants on plant and soil health *HN:A*	Conduct controlled experiments on biostimulants, emphasizing soil microbiology knowledge. Assess their potential as fertilizer alternatives and address regulatory constraints. Hypothesis-led lab trials followed by field trials are crucial for confirming efficacy. Ensure evidence-based regulation to instill farmer confidence.

P=policy, KE=knowledge exchange, A=applied, F/B=fundamental/basic, HN=high/normal, NL=normal/low, CH=critical/high

Table 4C Summary of Regenerative Agriculture Knowledge Gaps - Variety Development

Gap/Topic *Priority:Approach*	Key Comments - Survey/ChatGPT 40-word summary/*Discussion*
11. How to grow varietal blends effectively ***HN:A***	Integrate blend testing into AHDB RL trials. Utilize shared farmer experiences and supply chain support. Research blends' purpose and mechanisms. Develop practical guides and disseminate knowledge through farm clusters.
12. Breeding of crop varieties with enhanced disease & insect tolerance ***HN:F/B***	Breeders adapt to environmental changes, facing consumer opposition to GM. Research progresses, improving disease resistance, yet selective breeding takes time. Transition to regenerative agriculture may be gradual but necessary.
13. Variety evaluation with low/no plant protection products and/or reduced N application ***HN:A***	Collaborate with AHDB to enhance RL trials for field conditions. Utilize citizen science for multi-site replication. Conduct varietal trials in regenAg systems, demo applied research, and implement tramline trials. Focus plant breeding on low-carbon goals and establish a network of research farms.
14. The impact of variety blends on product quality and end-market use ***HN:A***	Increase on-farm research to understand practices across environments, crucial for market access. Support small supply chains to accommodate diverse food specs. Advocate for variety blends, addressing farmer concerns and aligning with consumer preferences. Exchange knowledge among farmers, possibly requiring policy intervention. *This is also a "food system" challenge; if variety blends impact on the quality of the final product and its potential uses, this needs to be evaluated using a food system approach.*
15. Variety evaluation that includes a description of rooting traits ***HN:A***	Collaborative on-farm research investigates root traits among varieties using rapid phenotyping, crucial for sustainable agriculture but requiring time alongside transitioning to regenerative practices.
16. How to enable use of landraces and other heterogenous material (e.g. plant populations). ***NL:All***	Expand variety options for regenerative agriculture, integrating landraces and populations in recommended list trials. Adapt seed regulations and establish market routes. Utilize genetics to enhance traits and transition to regenerative agriculture despite incomplete knowledge.
17. Evidence of the wider and indirect benefits of working with plant populations rather than single crop varieties or varietal blends. ***HN/NL:B/A***	Conduct hypothesis-led research to anticipate variety interactions and verify mechanisms. Overcome policy barriers with a 7-year experimental marketing period. Encourage farmer participatory breeding for population development. Ensure basic research for low farmer risk and address operational challenges for broader benefits.

P=policy, KE=knowledge exchange, A=applied, F/B=fundamental/basic, HN=high/normal, NL=normal/low, CH=critical/high

Table 4D Summary of Regenerative Agriculture Knowledge Gaps - Soil, Climate Change and Water Cycle

Gap/Topic *Priority:Approach*	Key Comments - Survey/ChatGPT 40-word summary/*Discussion*
SOIL PROCESSES & QUALITY	
18. Impact of changes in soil biology on weeds, particularly blackgrass *HN:A*	Study biology's effects on weeds under controlled conditions to quantify regenerative agriculture impacts. Share farmer experiences, enhance soil science, and promote mixed farming, especially on fenland soils. Address weed control challenges, particularly with blackgrass in regions reducing herbicide use. *Currently lots of fundamental science in the UK on beneficial microbes and plants. Likely to have big impact in low fertility soils - but value and interaction for temperate (less-weathered) soils in moderate/high input systems not well explored. Need for more fundamental science on how soils function. Need for really long-term studies to understand impacts of regen ag on soils and ecology*
19. Evidence of the impacts of mob grazing on soil and livestock health *HN:A*	Survey diverse grazing practices' impact on soil health, comparing nearby farms without such methods. Enhance interdisciplinary research, utilize case studies, and communicate findings through public forums. Conduct controlled trials and disseminate practical guides with farmer case studies. Prioritize evidence-building for dairy farming.
20. Lack of cost-effective soil health indicators addressing soil biological function *HN all*	Collaborative research with farmers to identify practical soil health indicators and assess scalability. Develop low-cost proxy measurements for regenerative practices. Address cost-efficiency and scalability to enhance adoption. Innovate soil biology and technology, such as indicator plants for symbiotic microbe assessment.
CLIMATE CHANGE MITIGATION, WATER CYCLE	
21. Evidence of the impacts of regenerative agriculture systems on the water cycle (flood risk, drought resilience) *HN:A*	Conduct catchment-wide studies on regenerative agriculture's landscape-scale impacts. Implement farm and catchment water monitoring with emphasis on landscape recovery. Expand long-term field trials investigating soil hydrology and disseminate existing work like Cranfield's for practical application.
22. Development of a clear farmland soil carbon code in the UK *CH/HN:P*	Compensating farmers for soil carbon in regen ag hinges on measurable metrics. Enhanced funding for soil research globally is vital, addressing measurement discrepancies. Long-term trials and policy frameworks are imperative to provide clear guidelines and develop effective monitoring, reporting, and verification (MRV) systems.

P=policy, KE=knowledge exchange, A=applied, F/B=fundamental/basic, HN=high/normal, NL=normal/low, CH=critical/high

Table 4E Summary of Regenerative Agriculture Knowledge Gaps – System Design

Gap/Topic *Priority:Approach*	Key Comments – Survey/ChatGPT 40-word summary/*Discussion*
23. Evidence to allow options for regenerative agriculture to be assessed in terms of wider impacts (e.g. whole life cycle analysis for input options) ***HN:A***	Policymakers require academic research, case studies, and multidisciplinary learning networks for informed decisions. Compile evidence and open farms to the public. Define regenerative agriculture rigorously for robust evidence. Highlight key farm activities and standardize sustainability assessment for consistent approaches. *Work on supporting system change by farmers; understanding antagonism of some farmers and barriers to change*
24. Evidence of the impacts of integration of legumes throughout the cropping system on N cycling including GHG emissions ***HN:A***	Ongoing research, including full LCA, examines legume impacts on emissions. Collaboration to pool existing knowledge is vital. Conduct field trials and develop remote sensing for GHG monitoring. Support legume benefits and study ecological interactions for comprehensive understanding and policy guidance.
25. How to design crop rotations to optimise economic and environmental benefits ***HN:A/KE***	Demonstration farms and knowledge events facilitate crop rotation understanding. Science offers comparative data, complementing farmer experiences. Share existing regenerative and agroecological crop rotation examples widely for holistic analysis. Long-term field experiments and decision tools predict outcomes from diverse crop combinations.
26. The impact of lower input use (N fertiliser and plant protection products) within regenerative agriculture on product quality and end-market use ***HN:A***	Understanding product quality impacts of regenerative agriculture is essential for market access and farmer input cost reduction. Collaborative research with farmers, commercial producers, and trials comparing conventional vs. regenerative methods are crucial for evaluating quality attributes and meeting market requirements. *As described above (re: variety blends) this is also a "food system" challenge; lower rates of N fertiliser can mean that cereals such as wheat end up with lower protein contents; this could potentially lead to more feed-quality grain in the marketplace and less bread wheat.*

P=policy, KE=knowledge exchange, A=applied, F/B=fundamental/basic, HN=high/normal, NL=normal/low, CH=critical/high

Table 4F Summary of Regenerative Agriculture Knowledge Gaps - Social and Economic

Gap/Topic *Priority:Approach*	Key Comments - Survey/ChatGPT 40-word summary/*Discussion*
27. Understanding of the impact (and the factors affecting it) of regenerative agriculture systems on farm livelihoods ***CH:all***	Evidence of improved farm livelihoods through regenerative agriculture is vital for widespread adoption. Government involvement, economic support, and socio-economic research are crucial for understanding impacts and facilitating transitions. Farmer input on costs/benefits is essential for comprehensive assessment and policy formulation.
28. Evidence of the potential benefits and disbenefits of developing a certification scheme for regenerative agriculture ***HN:P***	Economic justification for regenerative agriculture is essential. Certification schemes might limit farmer autonomy. Farmer-led research and exploring labels' effectiveness are crucial. Defining regenerative agriculture consensus is necessary for certification. Social science research on adoption likelihood and barriers with or without certification is imperative.
29. Better understanding of the main socio-economic factors constraining uptake of regenerative agriculture ***CH:all***	Understanding farmer perspectives on regen ag adoption necessitates multidisciplinary research involving farmers and social scientists. Long-term trials incorporating socio-economic factors are essential to inform policy and overcome adoption barriers. Qualitative research and farmer engagement are crucial for effective policy formulation and support. *Payment schemes/incentives to drive system change*
30. The potential benefits and disbenefits of food manufacturers and retailers championing regenerative agriculture ***HN:all***	Understanding the impact of retailers and advertising on regen ag dissemination is crucial. Farmer input, consumer behaviour, and retailer support are key factors. Case studies and market research can shed light on effective strategies, despite power dynamics and farmer sentiments.
31. The impact of regenerative agriculture systems on food quality, particularly nutrient density ***HN:F/B***	Collaboration between farmers and researchers is key. Governments should prioritize food quality improvements to alleviate societal pressures. Establishing an evidence base for healthier soils producing healthier food is crucial, though challenging due to multifaceted factors. Nutritional research and evidence are essential for consumer demand and informed decisions.

P=policy, KE=knowledge exchange, A=applied, F/B=fundamental/basic, HN=high/normal, NL=normal/low, CH=critical/high

Annex 3 Search terms and outcomes for challenges covered by this study[105]

Unless otherwise indicated, Web of Science searches took place in May 2024. Outcomes may be slightly different if the search were refreshed now, as new publications are constantly being added to the database.

Table 16 Outcomes of Web of Science searches for peer-reviewed literature related to defining regenerative agriculture (May 2024)

Code	Sub-challenge	Keywords (in TS=Topic, TI=title, AB=abstract, AK=author keywords)	Number
1.1	Defining regen ag/metrics of regen ag	TS=("regenerative farming" OR "regenerative agriculture" OR "regen ag")	351
		(TS=("regenerative farming" OR "regenerative agriculture" OR "regen ag")) AND TS=("definition" OR "meaning" OR "metric")	19
		screen and remove non-relevant papers manually	12
1.2	Regen ag standards/certification (pros and cons)	TS=("regenerative farming" OR "regenerative agriculture" OR "regen ag")	351
		AND "standard" OR "certification" OR "regulation" (Topic)	26
		screen and remove non-relevant papers manually	5

Table 17 Outcomes of Web of Science searches for peer-reviewed literature related to growing root crops in regenerative systems (May 2024)

Code	Sub-challenge	Keywords (in TS=Topic, TI=title, AB=abstract, AK=author keywords)	Number
2.1	Growing root crops in regen systems	(TS=("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"))	11,079
		TS=("carrots" OR "potatoes" OR "turnips" OR "swedes" OR "radishes" OR "beets" OR "rutabagas")	27,806
		no-till & root crop	32
		in English	30
		manual screening for relevance	13
		in the UK	0

105 Note that in all cases the number of papers identified is provided as a general indication of the volume of peer-reviewed research in the topic area; this number will vary slightly depending on the date of the search and specific keywords used.

Table 18 Outcomes of Web of Science search for studies on intercropping including companion planting and living mulches (May 2024)

Code	Sub-challenge	Keywords (in TS=Topic, TI=title, AB=abstract, AK=author keywords)	Number
2.2	Intercropping successfully	TS=(intercropping OR "mixed cropping" OR polyculture OR interplanting OR multi-cropping OR "strip cropping" OR "relay cropping")	14,906
		TS=(arable OR cereal OR rapeseed OR canola OR wheat OR barley OR oats OR beans OR maize)	586,056
		intercropping & arable	6,475
		in English	6,225
		in the UK	267
2.3	Companion planting successfully	intercropping & arable & companion planting in the UK	6
2.4	Using living mulches successfully	(TS=("living mulch" OR "permanent ground cover" OR "living cover" OR "perennial cover"))	671
		in English	649
		in the UK	17

Table 19 Outcomes of Web of Science search for studies on cover crops (May 2024)

Code	Sub-challenge	Keywords (in TS=Topic, TI=title, AB=abstract, AK=author keywords)	Number
2.5	Termination of cover crops; without herbicide; impacts on following crop	(TS=("cover crop" OR "catch crop" OR "green manure"))	10,598
		TS=(termination OR destruction)	290,632
		cover crop & termination	505
		ordered by relevance and first 50 screened for focus on termination method	20
		UK countries	8
2.6	Regionally adapted cover crops; cool, wet climates; temperate	TS=("cold tolerance" OR "frost tolerance" OR "cold hardiness" OR "chilling tolerance" OR "freeze resistance" OR "low-temperature tolerance" OR "frost hardiness" OR "cold resilience")	13,725
		cold tolerance and cover crops	18
		UK countries	0
2.7	Impacts of cover crops on pests	TS=(("pest control" OR "pest incidence" OR "pests" OR "disease control" OR "disease incidence" OR "disease" OR "insect control" OR "insect incidence" OR "insects" OR "weed control" OR "weed incidence" OR "weeds"))	5,136,792
		And cover crops	2,113
		UK countries	32

Table 20 Outcomes of Web of Science search for studies on additional agronomic challenges (May 2024)

Code	Sub-challenge	Keywords (in TS=Topic, TI=title, AB=abstract, AK=author keywords)	Number
2.8	Reducing herbicide use in regen systems	TS=("regenerative farming" OR "regenerative agriculture" OR "regen ag")	351
		TS=(herbicide)	73,186
		regen ag & herbicide	12
2.9	Integration of livestock into arable regen systems	TS=("livestock" OR "animal")	857,166
		livestock & regen ag & arable crops	11
2.10	Design of crop rotations for regen systems	TS=(crop rotation)	25,860
		crop rotation & regen ag	39
2.11	Design of equipment for regen systems	TS=(equipment OR machinery)	496,123
		regen ag & equipment	2

Table 21 Outcomes of Web of Science search for studies on crop genetics (May 2024)

Code	Sub-challenge	Keywords (in TS=Topic, TI=title, AB=abstract, AK=author keywords)	Number
3.1	Breeding & evaluation for disease and insect tolerance	TS=(arable OR cereal OR rapeseed OR canola OR wheat OR barley OR oats OR beans OR maize)	586,056
		TS=("disease" OR "pest" OR "pathogen" OR "insect" OR "fungus" OR "virus")	6,120,037
		TS=(breeding OR genetics OR gene)	4,020,505
		arable AND disease AND breeding	23,920
		AND wheat only	11,284
		in the UK	737
3.2	Breeding & evaluation for root traits	arable AND (TS=(root OR rhizosphere)) AND TS=(breeding OR genetics OR gene)	15,252
		AND wheat only	6,304
		in the UK	381
3.3	Breeding & evaluation for low N inputs	TS=("low N" OR "low nitrogen" OR "nitrogen use efficiency" OR "N use efficiency" OR "NUE")	23,991
		arable AND low N AND breeding	1,281
		AND wheat only	632
		in the UK	69
3.4	Breeding & evaluation for weed competitiveness	TS=("weed competition" OR "weed suppression" OR "allelopathy")	9,155
		Weed competition AND breeding AND Arable	188
		AND wheat only	129
		in the UK	6
3.5	Breeding & evaluation for performance in reduced tillage intensity systems	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*"	25,126
		arable and tillage and breeding	389
		AND wheat only	257

Table 22 Outcomes of Web of Science search for studies on genetically diverse crops (May 2024)

Code	Sub-challenge	Keywords (in TS=Topic, TI=title, AB=abstract, AK=author keywords)	Number
3.6	How to effectively grow variety blends	TS=(("variety mix*" OR "variety blend" OR "genotype mix*" OR "genotype blend"))	286
		mix and arable	119
		in the UK	23
3.7	Impacts of variety blends on crop quality & markets	TS=(quality)	3,604,443
		quality and mix and arable	24
3.8/3.9	Heterogeneous plant materials - how to enable their use/evidence of impacts on and off-farm	TS=("composite cross population" OR "landrace*" OR "heirloom variet*" OR "heritage variet*" OR "evolutionary plant breeding")	19,081
		populations and arable	5,658
		populations without landrace and arable	64
		in the UK	10

Table 23 Outcomes of Web of Science searches for peer-reviewed literature related to soil health (May 2024 unless otherwise indicated[106])

Code	Sub-challenge	Keywords (in TS=Topic, TI=title, AB=abstract, AK=author keywords)	Number
4.1	Better indicators of soil biological function	TS=("soil quality" OR "soil health")	22,142
		TS=("biology" OR "microbiology" OR "ecology" OR "microbial")	1,194,103
		TS=("indicator" OR "metric" OR "test")	3,958,262
		soil health AND biology AND indicator	963
		in the UK	36
4.2	Impacts of soil biology on weed populations (blackgrass)	TS=("weed population*" OR "weed pressure" OR "weed competition")	3,717
		weeds and soil health	88
		weeds and soil health and microbiology	21
4.3	Mob grazing impacts on soil health	TS=("mob grazing" OR "multi-paddock grazing" OR "cell grazing" OR "intensive rotational grazing" OR "holistic planned grazing" OR "management intensive grazing")	267
		grazing and soil health	17
		in the UK	3
4.4	Impacts of biostimulants on soil health	TS=(biostimulant* OR biofertiliser* OR biofertilizer*)	
		biostimulants and soil health	411
		in the UK	5
4.5	Impacts of strategic (occasional) tillage on soil health vs glyphosate	TS=("strategic till*" OR "occasional till*")	100
		strategic tillage and soil health	25
		in the UK	1
		TS=("glyphosate" OR "Round-Up")	18,189
		Glyphosate and soil health	143

[106] Glyphosate reference list updated October 2024

Table 24 Outcomes of Web of Science searches for peer-reviewed literature on wider system considerations for regenerative agriculture (October 2024)

Code	Sub-challenge	Keywords (in TS=Topic, TI=title, AB=abstract, AK=author keywords)	Number
5.1	Impacts of regenerative agriculture systems on the water cycle (flood risk, drought resilience)	TS=("regenerative farming" OR "regenerative agriculture" OR "regen ag")	374
		TS=(water OR drought OR flood)	4,018,919
		regen ag AND water	99
		Review articles only	24
5.2	Impacts of integration of legumes throughout the cropping system on N cycling including GHG emissions	(TS=(legum*)) AND TS=(crop rotation)	3,012
		TS=("greenhouse gas" OR "GHG" OR "emissions" OR "climate change")	800,252
		legume & GHG	458
		Review articles only	58
5.3	Practice and options for regenerative agriculture to be assessed in terms of wider impacts	TS=(("regenerative farming" OR "regenerative agriculture" OR "regen ag"))	436
		TS=("Social Life Cycle Assessment" OR S-LCA OR "Social Life Cycle Analysis" OR "Social Sustainability Assessment")	711
		Regen ag AND S-LCA	0
		TS=("Environmental Life Cycle Assessment" OR LCA OR "Life Cycle Analysis" OR "Environmental Life Cycle Impact Assessment")	37,083
		Regen ag AND LCA	9

Table 25 Outcomes of Web of Science searches for peer-reviewed literature on product quality effects for regenerative agriculture (October 2024)

Code	Sub-challenge	Keywords (in TS=Topic, TI=title, AB=abstract, AK=author keywords)	Number
5.5	Impact of regenerative agriculture systems on food quality, particularly nutrient density	TS=("Nutrient density" OR "Nutritional content" OR "Nutritional profile" OR "nutritional quality")	24,992
		Nutrient density AND regen ag	6