Crop and Soil Science Research Priorities and Knowledge Gaps with a Regenerative Agriculture Focus

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Outcomes of the Rapid Evidence Assessment to map UK crop science research with a Regenerative Agriculture focus

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Background & Aims

This report summarises the outcomes of the Rapid Evidence Assessment (REA) to Map UK crop science research with a Regenerative Agriculture focus commissioned by the Aurora Trust, The Mark Leonard Trust and the Gatsby Charitable Foundations. This rapid evidence assessment aimed to provide a quick overview of the state of knowledge and research activity on a number of topics important for the development of regenerative agriculture in the UK, with a particular emphasis on priorities for farmers. The goal was to prioritise research topics and identify where the current gaps in knowledge exist so that future funding can be targeted towards topics that have previously been insufficiently studied.

A key component of this project was the Cambridge Future of Agriculture conference, which served as a unique platform for farmers, farmer organisation representatives, and scientists to openly discuss and shape future research needs; these are reflected in this report. It also includes insights from stakeholder conversations, an online workshop, a comprehensive review of ongoing and past UK projects, and a rapid synthesis of peer-reviewed literature.

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

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

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[1] https://www.theccc.org.uk/publication/agroecology-a-rapid-evidence-review-university-of-aberdeen/

[2] See all three reports from: Evaluating the productivity, environmental sustainability and wider impacts of agroecological compared to conventional farming systems project SCF0321 for DEFRA. 20 February 2023

Approach

To conduct this REA we began by drafting a list of research priorities based on informal conversations with key stakeholders and reviews of prior research prioritisation exercises. We then held an online workshop with stakeholders (19 in total) to help rank the priorities and discuss best approaches to conduct the research. This was followed by a detailed scoping study of ongoing and past projects in the UK which were mapped to the list of research priorities. In parallel, searches of published academic literature were conducted and a selection of papers on each topic were rapidly reviewed and synthesised. Finally, the results were briefly presented at the Future of Agriculture Conference in Cambridge during March 2024.

Key Findings

A total of 34 priorities were identified in the study which were grouped into these six challenge areas.

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

A more detailed discussion of each of these challenges areas and priorities is included in Appendix A.

Table 1 summarises the topics that received more than 10 votes in the critical or high-importance categories across the six challenge areas. The topics have been further ranked based on the number of peer-reviewed papers found on the Web of Science (<20 indicating minimal research activity globally on this topic) and the 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 how socio-economic factors affect 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, which was 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, 2.5 Termination of cover crops, 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 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.

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.

Conclusions

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 (see Table 1) 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.

Candidate areas for future research include:

- Selection and breeding of cover crops and development of management systems that allow their benefits to be maximised in the UK environment.
- Selection and breeding of arable crops for diversified cropping systems (including intercropping and living mulches) with lower external inputs.
- Quantification of the benefits, including environmental and nutritional, of regenerative agriculture systems.
- Improved understanding of the impacts of tillage on soil health and how this contrasts with potential negative effects of herbicide use.
- Real data on the economic implications for farm businesses of adopting a regenerative agriculture approach.

Further details on each priority area are outlined in Appendix A. A full report on this project and the database listing projects and reports will be available subsequently.

Table 1 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. Other topics mentioned in this document are summarised in Appendix A. 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. A similar table with remaining topics is in Appendix B. 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

Authors Recommendations & Next Steps

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

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

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

Appendix A

Challenge 1: Standardisation of regenerative agriculture

1.1 Identification of metrics to support definition

Researchers are concerned that conducting robust comparative studies will be challenging without a clear definition of regenerative agriculture. However, there is some indication that there are also benefits to a broad definition, especially for supply chain actors. Various authors and projects have offered definitions of regenerative agriculture; for example, the Great project in Gloucestershire proposed this definition:

> *Farming principles and practises 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.*

1.2 Regenerative agriculture standards/certification (pros and cons)

Debate about certification schemes is not a research question. The pros and cons of different types of schemes are covered in this project's supplementary information.

While identified as important topics for policy development in the evidence review, neither of these topics emerged as top priorities from farmers; further academic studies may help to resolve discussions around the need for a definition and metrics for regenerative agriculture and the case for certifications schemes.

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

Although implementation of regenerative agriculture practices is underpinned by agreed principles, there is no locally tailored independent information to support an individual farm business implementing regenerative agriculture. This overarching challenge emerged clearly from the workshop and throughout the conference. Knowledge exchange between practice and science, coupled with targeted applied research and demonstration, is key to address the challenge. There is little interaction between empirical observers at field and farm scale and the scientists undertaking detailed studies of mechanisms at gene and cellular scale. There is also often a mistrust of science within the community of regenerative agriculture practitioners largely arising from a misunderstanding of the practice of science, which can appear remote and overly reductionist. The facilitation of co-production approaches with appropriate reward for all participants, especially farmers, will be essential to enable this challenge to be

addressed effectively (discussion from floor at Future of Farming conference). Effective integration of outputs within an independent framework for knowledge exchange will also be crucial.

The development of advice and guidance to support implementation of specific regenerative agriculture practices is best addressed through targeted on-farm experiments with trial networks that promote knowledge exchange within the agricultural community. Farmer clusters are an excellent way to facilitate this research approach, though stable funding is essential (Robert Fraser, Future of Farming conference). The Soil Association's Innovative Farmers program uses this approach but has relied on philanthropic funds to continue (Helen Browning, Future of Farming conference). The AHDB Monitor and Strategic farm networks offer good opportunities to trial practices on real farms and collect useful data (Mike Gooding, Amanda Bennett, Henrietta Lowth, AHDB). Several long-term, controlled experiments directly informed by local farming practice, such as the Fix Our Food experiment at Leeds University (presented by Ruth Wade at the Future of Farming conference), address many practical challenges listed here (see supplementary material for a full list).

2.1 Growing root crops in regenerative 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

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

This biological approach to pest management has previously received relatively little attention. While not identified as a top priority, there is a need for more fundamental

research (understanding mechanisms) and applied research and knowledge exchange to improve guidance on this approach. We recommend forming an expert group to design a comprehensive program that includes fundamental and applied research and knowledge exchange, such as farmer case studies. Involving crop breeders in selection of specific varieties better suited as companion crops will also be crucial.

2.4 Using living mulches successfully

Using perennial covers (living mulches) in arable systems is a key strategy to reduce reliance on herbicides, particularly glyphosate. This topic was scored 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.

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

Exploring mechanical methods of terminating cover crops is crucial for reducing reliance on glyphosate. This area is a **high priority for applied**. 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

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

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

New programs should capitalize on 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. 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 regenerative systems

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.

2.10 Design of locally-adapted crop rotations for regenerative systems

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

2.11 Design of equipment for regenerative systems

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 genetic resources

In the past, crop selection and breeding programs have primarily focused on yield improvement and quality traits together with pest and disease resistance, but regenerative agriculture farmers are interested in a broader range of traits. Stephanie Swarbreck presented her work on "Exploiting novel wheat genotypes for regenerative agriculture" at the Future of Agriculture conference, which aims to identify the traits needed as well as new varieties suited for these systems. The AHDB has also attempted to address this by regularly reviewing recommended list trials. Better use of crop genetic resources and crop breeding to integrate new traits are both important, though a crop breeding approach may take decades before benefit is seen on farm. Action to address the following challenges (3.1 to 3.5) would need to include

fundamental research in plant science alongside trials in different environments and management conditions. Farmer participation in the breeding process, from the early stages when desirable traits are identified, should ensure that varieties are developed aligned with the regenerative agriculture sector's needs.

3.1 Breeding and evaluation for disease and insect tolerance

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.

3.2 Variety evaluation and breeding for root traits

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 (3.7) and in reduced tillage intensity systems (3.5) were identified as high priorities, and in programmes addressing those targets would include consideration of root traits.

3.3 Variety evaluation and breeding for low N and pesticide inputs

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

Competitiveness against non-crop plants, including weeds and living mulches, is crucial in regenerative agriculture crops. Speed of emergence and leaf characteristics 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 selected 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 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 lie in breeding for reduced tillage intensity in species apart from wheat.

3.6 Selection and agronomy of variety blends

The AHDB already offers 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. 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 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 program, should provide valuable insights for future projects. This work could be linked with challenge 3.6.

3.8 Heterogeneous plant materials[3] - how to enable their use

These materials represent a higher genetic diversity level in the field than variety blends. 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. 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. 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

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 from seed certification to use within the 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

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

[3] Includes landraces, composite cross populations, heritage varieties and heirloom varieties.

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.

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

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). Addressing this question requires a multidisciplinary approach that includes on-farm studies and fundamental biology.

4.3 Mob grazing impacts on soil health

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

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 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

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 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

The challenges listed so far have been focussed within the farm boundaries. There is also need to assess the impacts of regenerative agriculture on the wider food system and on the environment beyond the farm-gate. Here wider multidisciplinary stakeholder teams are needed to give the research context and also to ensure that novel research approaches and innovative solutions are applied to the study of regenerative systems. Whilst these challenges lie beyond the ability of plant and soil science to tackle them alone, nonetheless it is important both that the multidisciplinary teams tackling the challenges are enabled by the latest plant and soil science, and also that research teams tackling the earlier challenges are informed by these research outcomes.

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

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. 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

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. 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.

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)

Exploring the impacts of transitioning towards regenerative agriculture at the landscape scale is crucial to understand 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). This is a **high-priority area for basic and applied research** and will require multidisciplinary studies involving environmental modelers and policymakers. 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.

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

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.

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

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

Challenge 6: Socio-economics

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

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

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.

Appendix B

Summary table of lower priority research topics based on outcomes of the stakeholder workshop 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 the highest priority/largest gap (green), moderate priority/gap (amber) and lower priority/smaller gap (putty).

		Workshop Outcomes		Scoping Study Outcomes			
		Critical+High Votes <=10	Research Type	Peer-reviewed papers	Ongoing projects (total 27)	Past projects (total 28)	Grey literature (total 76)
2.3	Companion planting successfully	10	Applied/KE	>100	2	2	5
2.4	Using living mulches successfully	10	Applied	>100		4	3
2.10	Design of locally-adapted crop rotations for regenerative systems	10	Applied/KE	20-100	4	3	21
5.5	Impact of regenerative agriculture systems on food quality, particularly nutrient density	9	Basic	<20	2		
1.2	Regen ag standards/certification (pros and cons)	9	Policy	<20			1
4.3	Mob grazing impacts on soil health	8	Applied	<20	1		1
4.1	Better indicators of soil biological function	7	Basic/Applied	>100		1	8
3.2	Variety evaluation and breeding for root traits	7	Applied	>100		2	3
3.7	Impacts of variety blends on crop quality and markets	7	Applied	20-100		1	0
4.4	Impacts of biostimulants on (plant and) soil health	7	Applied	>100		1	1
3.1	Breeding and evaluation for disease and insect tolerance	6	Basic	>100	3	2	19
3.6	Selection and agronomy of variety blends	6	Applied	>100	1	2	
3.9	Heterogeneous plant materials – evidence of impacts on and off-farm	6	Applied	20-100			
3.8	Heterogeneous plant materials - how to enable use	5	Applied	20-100	1	2	1
2.11	Design of equipment for regenerative systems	0	NA	<20			2