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

Challenge 3 (of 6): Crop genetic resources

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Challenge 3: Crop genetic resources

Thank You

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Introduction

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

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

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

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

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

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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

Key Findings

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

The six challenge areas identified were:

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

This publication presents the findings of Challenge 3: Crop genetic resources. The findings of the other challenges can be found in the associated series of publications available at www.organicresearchcentre.com.

3.1 Breeding and evaluation for disease and insect tolerance

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.

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. Nineteen projects relating to this topic were identified in a search of past Defra projects (Table 1). 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(3) (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, cropping systems e.g. beans, linseed, peas.(4)

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3. https://designingfuturewheat.org.uk/about/

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

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(5) 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(6) 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

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

6. https://liveseeding.eu/

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 1 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 1).

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(7) 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

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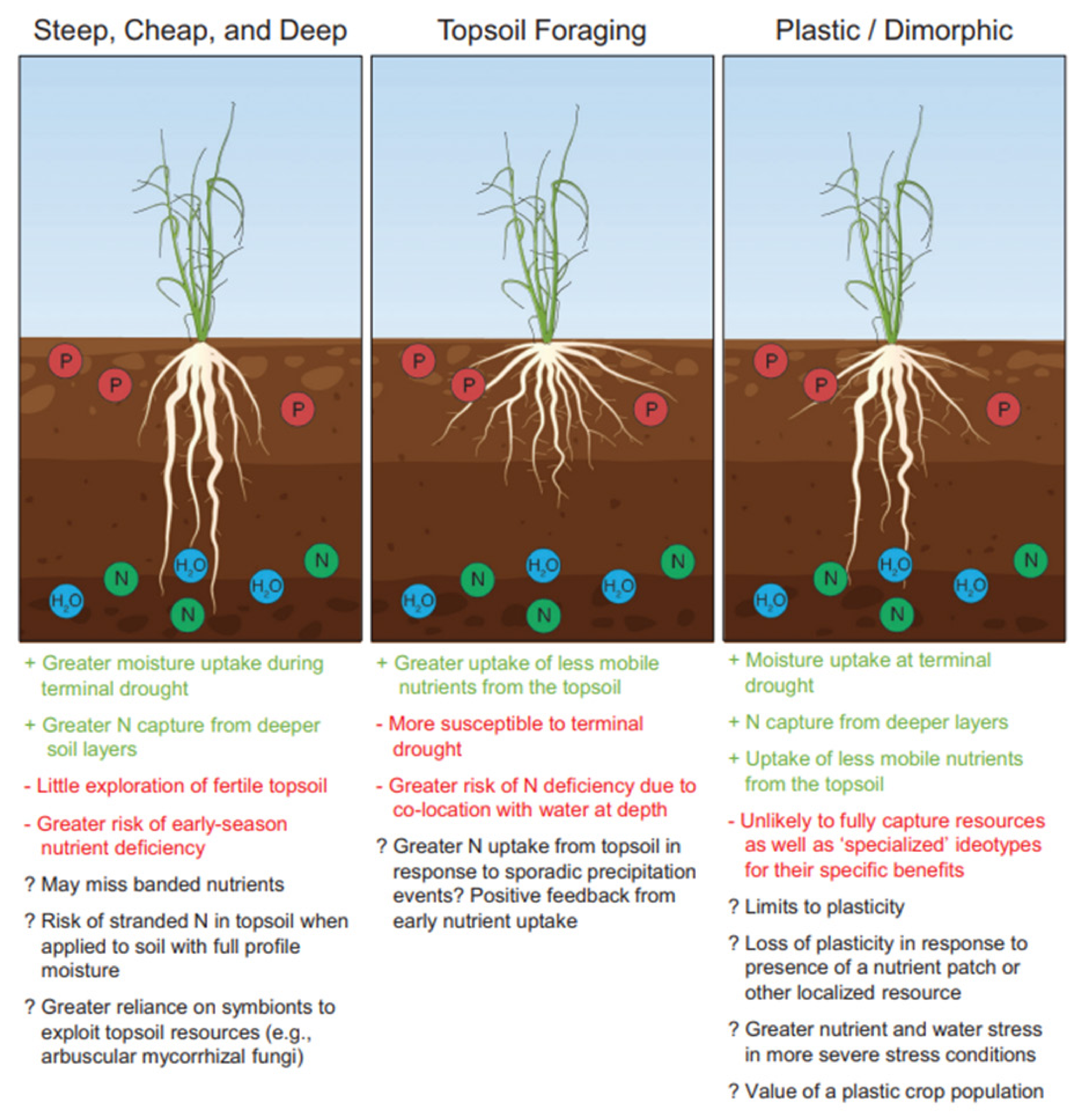
7. A mutualistic relationship is a type of symbiotic relationship that is beneficial to both species involved.

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.

Figure 1 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)



Steep, Cheap, and Deep

- \+ Greater moisture uptake during terminal drought
- \+ Greater N capture from deeper soil layers
- \- Little exploration of fertile topsoil
- \- Greater risk of early-season nutrient deficiency
- ? May miss banded nutrients
- ? Risk of stranded N in topsoil when applied to soil with full profile moisture
- ? Greater reliance on symbionts to exploit topsoil resources (e.g., arbuscular mycorrhizal fungi)

Topsoil Foraging

- \+ Greater uptake of less mobile nutrients from the topsoil
- \- More susceptible to terminal drought
- \- Greater risk of N deficiency due to co-location with water at depth
- ? Greater N uptake from topsoil in response to sporadic precipitation events? Positive feedback from early nutrient uptake

Plastic / Dimorphic

- \+ Moisture uptake at terminal drought
- \+ N capture from deeper layers
- \+ Uptake of less mobile nutrients from the topsoil
- \- Unlikely to fully capture resources as well as 'specialized' ideotypes for their specific benefits
- ? Limits to plasticity
- ? Loss of plasticity in response to presence of a nutrient patch or other localized resource
- ? Greater nutrient and water stress in more severe stress conditions
- ? Value of a plastic crop population

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)(8) (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

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8. https://www.rothamsted.ac.uk/project/wheat-genetic-improvement-network

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 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(9) 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 (N2 or the greenhouse gas N2O).

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(10).

9.This included soil N supply and fertilizer N

10. https://designingfuturewheat.org.uk/about/

Past projects that have addressed NUE in UK crops are listed in Table 2. 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(11). 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:

> 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 2 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

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11. Maris Widgeon was introduced in 1964, Avalon 1980, Hereward 1991 and Solstice 2002

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(12) and SolACE(13). In both of these projects different varieties of the crops included (in the case of SolACE: potatoes, maize, wheat) were assessed 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(14) 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.

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

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

14. Impact of nutrient scenarios on the performance of cereals and oilseeds varieties (scoping review) I AHDB

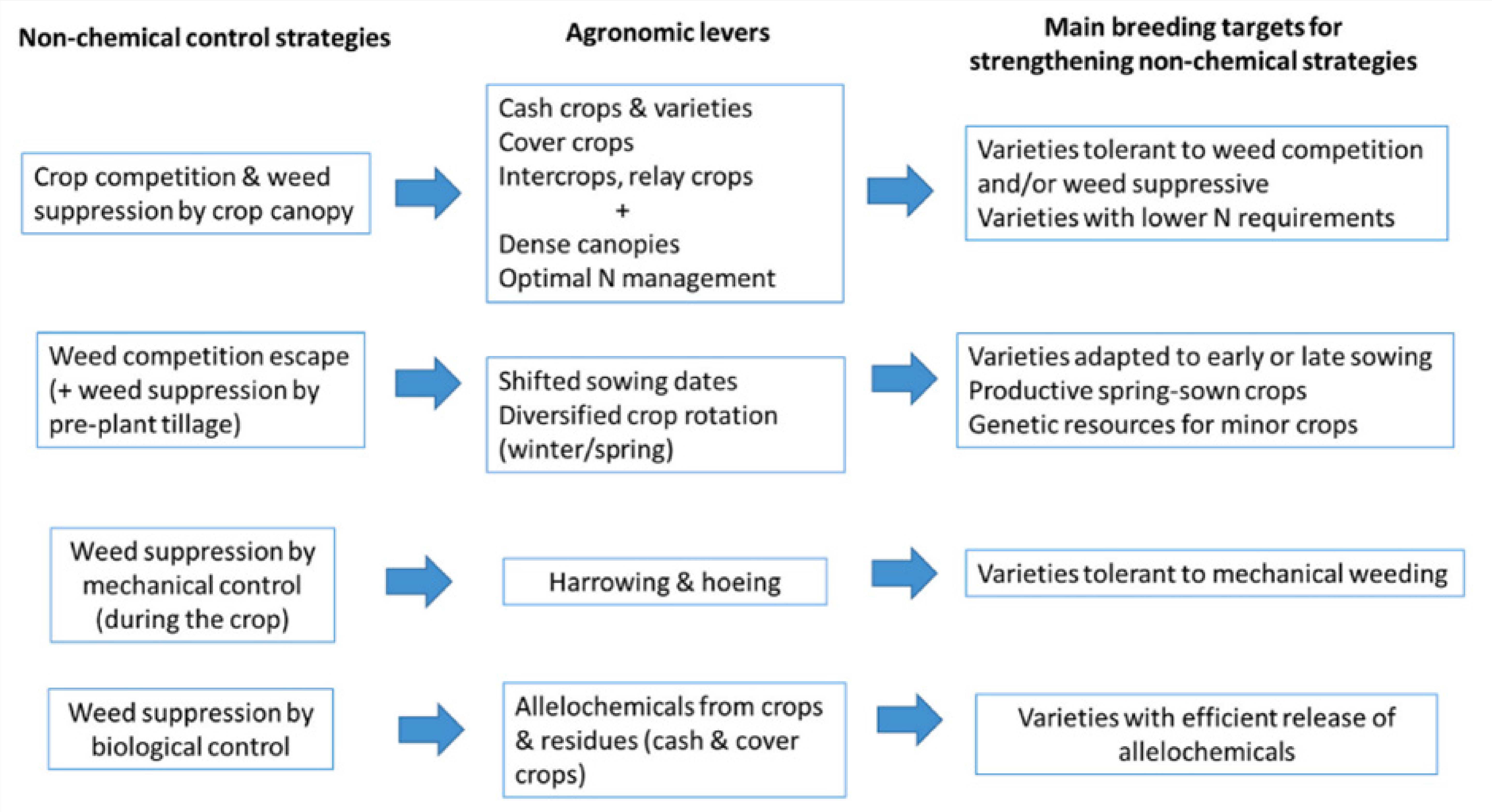
Crop varieties capable of efficiently accessing nitrogen from inaccessible soil reserves, such as organic forms of nitrogen and inorganic nitrogen deeper in the soil profile, and utilizing it effectively, can potentially reduce the demand for fertilizer nitrogen in the future. N uptake efficiency traits 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 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 Challenge 2.3) and living mulches (see Challenge 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" 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 2 summarises the main breeding targets for strengthening non-chemical strategies.

Figure 2 Non-chemical weed control strategies, agronomic levers and main breeding targets. From Debaeke et al. 2024



Allelopathy (see Challenge 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(15) 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.

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

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 ranking of varieties in the RL trials which are conducted using conventional tillage practices, would be the same under reduced tillage intensity(16).

The recent RL review(17) identified establishment technique(18) 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.

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

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

18. Presumably this refers to methods like direct drilling/no-till.

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. 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(19). 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.

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19. Refer to the paper for a detailed list of these traits.

There are few projects in the UK that have explored GxT interactions; however, the new NIAB project: Exploiting novel wheat genotypes for regenerative agriculture(20) 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.

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20. Exploiting novel wheat genotypes for regenerative agriculture I 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. 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(21) and SolACE(22) 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(23) (2020-21) and now through the Horizon Europe Project LiveSeeding(24). 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.

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

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

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

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

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 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 Challenge 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 grow 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(25) and H3(26) (Healthy Soil, Food, People) are exploring the food system impacts of a transition to regenerative farming and should provide useful insights into this question.

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25. https://fixourfood.org/
26. https://h3.ac.uk/

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.

3.8 Heterogeneous plant materials(27) – 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).

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)

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(28) 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(29)). This report should be read for an in-depth discussion about this subject area. It includes a useful summary of

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27. 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.

28. https://www.ukgrainlab.com/

29. The report is still under review by Defra.

outstanding questions for research and development. Several of these are relevant to enabling their use. These include:

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

Project Summary

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

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

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

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

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

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

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.

Author Recommendations

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

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

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

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

Appendix A

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

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

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