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

Challenge 4 (of 6): Soil Health

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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 4: Soil Health. The findings of the other challenges can be found in the associated series of publications available at www.organicresearchcentre.com.

4.1 Better indicators of soil biological function

Maintenance of soil health through feeding and supporting a diverse soil microbial population is the foundation of regenerative farming systems. The regenerative farming community are particularly interested and engaged with the concept of "soil biology" and in many cases have pursued additional qualifications (e.g. Dr Elaine's™ Soil Food Web courses(3), Nicole Masters' courses in soils offered through Integrity Soils(4)). These courses focus on assessing populations of fungi, bacteria and microfauna (e.g. protozoans), as well as root colonisation by arbuscular mycorrhizal fungi (AMF) using techniques in basic microscopy; some laboratories also offer these assessments, e.g. Envirolizer(5). In parallel with growth in on-farm microbial community assessment techniques, rapid DNA-based methods for fingerprinting soil microbial communities have been developed and are offered by some laboratories (e.g. Fera Sciences "Big Soil" project(6), NatureMetrics eDNA(7)).

The AHDB conducted extensive research into indicators of soil health including biology in the Soil Biology and Health Partnership(8) (2017-2022). They highlighted the gap between the range of indicators for soil biology developed by the research community and the guidance needed to use these indicators to make management decisions on farm. They reviewed and evaluated molecular (DNA) approaches to analysing soil health providing a useful, robust analysis of the value of these techniques for on-farm decision-making (Elphinstone et al. 2018; Dussart et al. 2023). The recommendation from their work on molecular techniques was that: "With no robust UK benchmarks for biological communities (and DNA-based testing costly), the research did not recommend using such approaches for the routine monitoring of soil health."

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3. https://www.soilfoodweb.com/about/
4. https://integritysoils.com/
5. https://envirolizer.com/soil-fertility/soil-analysis/
6. https://www.fera.co.uk/crop-health/introducing-the-big-soil-community
7. https://www.naturemetrics.com/?gad_source=1&gclid=Cj0KCQjwsPCyBhD4ARIsAPaaRf37GWSloyJQfoJfxVcPzKiMUD158aaHb-bp78D1FvOOCmWLVE1EbQAaApGrEALw_wcB
8. Soil Biology and Soil Health Partnership | AHDB

To create the shortlist of indicators of soil health, a selection of 13 potential biological indicators were ranked by experts using a logical sieve approach that scored each indicator based on relevance to agricultural and environmental impact and practicalities of use. The list of indicators reviewed at this stage included the DNA-based techniques mentioned above (microbial community structure and diversity) and some of the measures used by the Soil Food Web practitioners, e.g. AMF root colonisation, total fungi and bacteria, nematode communities. However, none of these were included in the final shortlist of biological indicators in AHDB's Soil Health Scorecard(9) with only microbial biomass, earthworms and respiration selected. The current version of the scorecard only lists earthworms as a biological indicator, although some commercial laboratories are offering a more complete soil health check that includes the Solvita CO2 burst test, a measure of soil respiration that integrates the size and function of the microbial community with the availability of carbon sources in the soil. Recently the UK Centre for Ecology and Hydrology launched a web-based tool for assessment of soil health(10) that builds on the AHDB Soil Health Scorecard approach. This tool allows the user to benchmark their soils against others across the UK from similar land uses and soil types. It uses just four indicators of soil health: organic matter, earthworm counts, pH and bulk density.

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

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

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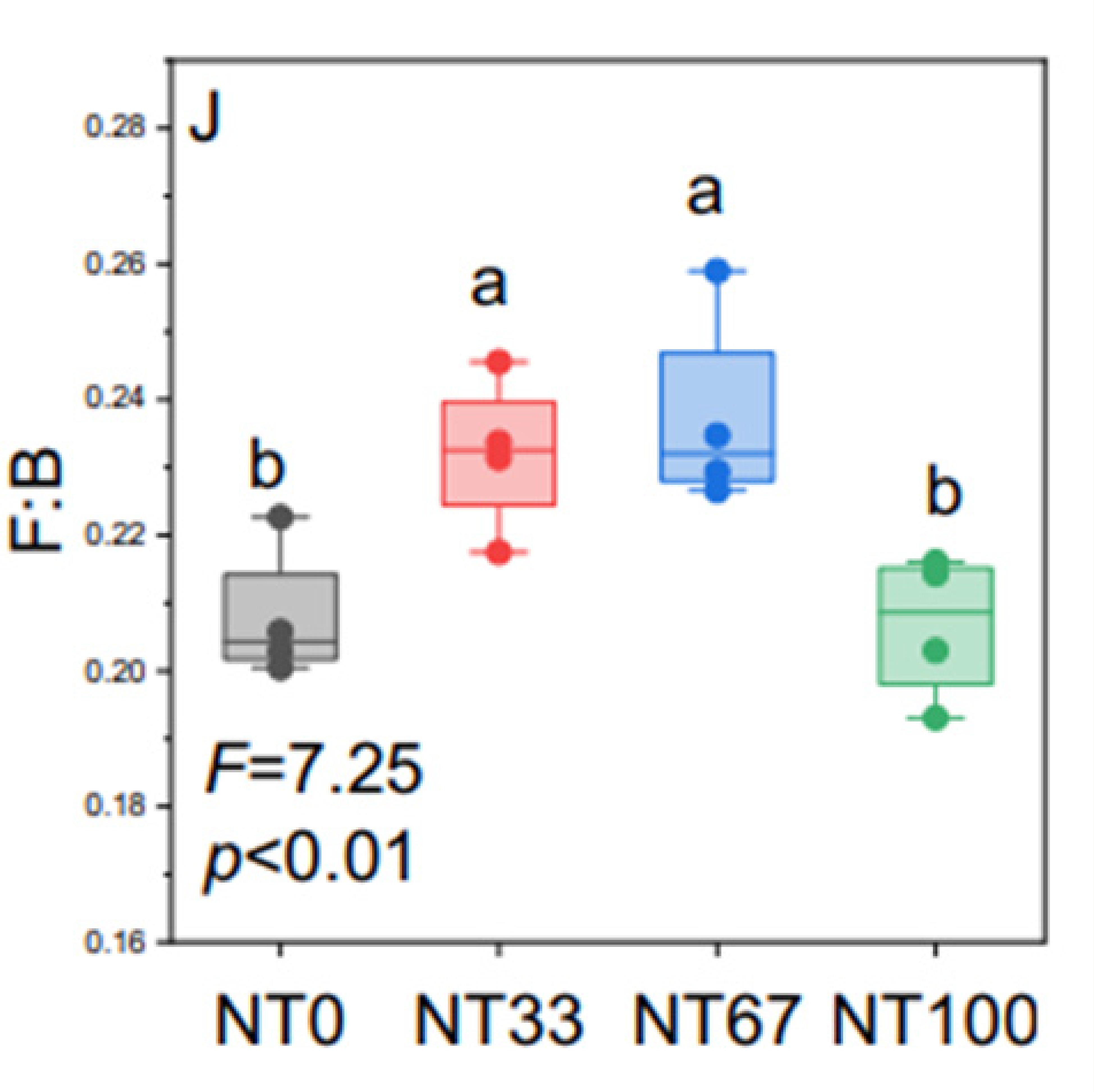
9. https://ahdb.org.uk/knowledge-library/the-soil-health-scorecard
10. https://connect-apps.ceh.ac.uk/soilhealth/

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

Figure 1 Extracted from Zhu et al (2023) showing fungal to bacterial ratios measured using PLFA for soils under no-till management with 0% (NT0), 33% (NT33), 67% (NT67) or 100% (NT100) of corn stover retained in the field.



compared to bacteria". But this conclusion is confounded by the fact that the crops themselves contribute more carbon than a fallow system. Zhu et al. (2023) also used PLFA to determine fungal and bacterial biomasses and F/B (Figure 1). They showed that ratios were similar when either no or all of the corn stover was retained in an 8-year study of corn grown in monoculture. This demonstrates the difficulty of interpreting results of F:B; in the same study more direct measures of soil health like soil C and N and dissolved organic carbon were all significantly higher when corn residues were retained but these important differences were masked by the F:B ratio. Like many of the other biological indicators discussed above, the challenge with F/B is in relating it to soil functions and using it to make management decisions. Without the establishment of thresholds, which will likely vary with management and a variety of soil properties (e.g. carbon contents, pH, soil texture), it is not possible to reliably use measures of soil F/B to make informed decisions on management.

Defra is committed to establishing a soil health indicator under its 25 Year Environment Plan Outcome Indicator Framework(11) and will be supporting farmers to establish their own soil health baseline. Recent projects(12) funded by Defra and UKRI are exploring new approaches to measuring soil biology and function under UK conditions.
The TRUTH project(13) tests PES Technologies' soil sensor which "sniffs" volatile compounds from the soil and links them to biological properties. Verdant Carbon in Kent is working with NIAB to develop an improved approach to assessing soil biological communities calibrated to UK conditions. These may result in more refined methods of assessing soil biological health. Outcomes of these projects should be reviewed before embarking on new research to develop better indicators of soil biological function.

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11. https://oifdata.defra.gov.uk/
12. For more information see soil health projects funded by the Defra Farming Innovation Programme https://www.ukri.org/news/funding-boosts-farm-resilience/
13. https://bofin.org.uk/truthproject/

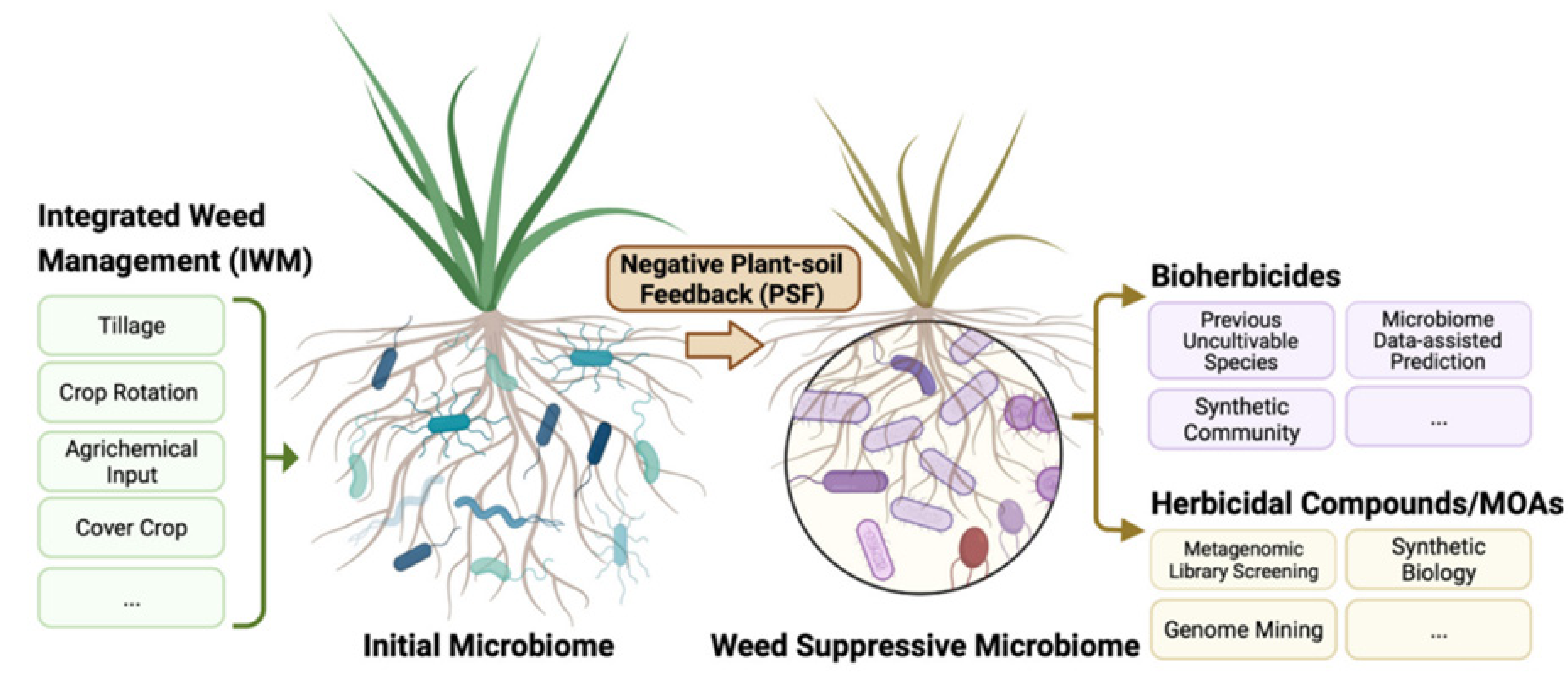
Maintaining soil biological health and function is a fundamental principle of regenerative agriculture. Farmers are eager to learn new ways to assess soil health on their farms. Soil biological indicators were evaluated as part of the AHDB Soil Biology and Soil Health Partnership (NIAB, ADAS, Fera, SRUC);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

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

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

Cheng et al. (2022) reviewed opportunities for microbiome suppression of weeds (see summary in Figure 2). While two of the methods they discuss are essentially alternatives to herbicides (microorganisms formulated as bioherbicides or application of the compounds produced by microorganisms that suppress weed growth), they also discuss field management practices (integrated weed management) that enhance microbiome function for weed suppression. It is this third method that is particularly interesting to regenerative farmers who are aiming to build healthy soils with healthy microbial populations to suppress weeds.

Figure 2 Schematic diagram illustrating approaches to harnessing the soil microbiome and negative plant-soil feedback to improve weed management in regenerative agriculture (copied from Cheng et al. 2022)



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

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

2. The use of soil microorganisms to immobilize excess nutrients that promote weed growth has been proposed as a strategy for weed suppression. The process of nitrogen immobilization through the addition of high-carbon materials, such as wood chips, is well-documented. Cheng et al. (2022) suggest that this approach can be managed to limit nutrient availability during periods when weed proliferation is most likely. However, the challenge lies in balancing the nutrient needs of the crop while restricting access to weeds. This concept may underlie the regenerative agriculture community's belief that

fungal-dominated soils suppress weed growth. Soils receiving significant inputs of woody material may foster unique fungal communities, but weed suppression in these soils may be less about direct fungal action and more about the role fungi play in immobilizing excess nutrients.

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

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

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

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

4.3 Mob grazing impacts on soil health

Mob grazing(14) is a term used to describe a range of management techniques that involve relatively frequent movement of grazing animals between paddocks with sward entry heights and exit heights taller than traditional set stocking or rotational grazing systems. The terminology describing these systems is varied which makes it challenging to identify evidence from peer-reviewed and grey literature. We used a variety of terms (mob grazing, multi-paddock grazing, cell grazing, intensive rotational grazing, holistic planned grazing, management intensive grazing) in our literature search to identify papers which have studied what is broadly understood to be mob grazing in the regen ag community. Only 17 papers linking mob grazing and soil health were identified, with just 3 of these published in the UK.

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

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

more carbon (e.g. forested landscapes). Their paper sets out to scrutinise some of the "remarkable claims about the extent to which anthropogenic carbon emissions may be mitigated by sequestration in pastures and rangeland" being made "outside the scientific mainstream".

Jordon et al. (2024) report that approximately 80% of European grassland soils are below their carbon saturation point, suggesting that there is potential through improved management to build carbon in these soils. However, they also report that the scientific evidence base for the relative effects of different pasture management regimes on soil carbon is limited and argue that more medium- and long-term studies are needed. In general, they predict gains in soil carbon on improved pastures in the UK if rotational grazing is used compared to set stocking, but find that the evidence base for claims about benefits from mob grazing (e.g. trampling of grass into the soil surface can increase soil organic matter in the topsoil) is limited and requires further research.

Some of the "remarkable claims" referred to by Jordon et al. (2024) are based on studies like the ones summarised in Table 1, but these results should be interpreted with caution. Of these seven studies, only one was conducted in the UK, so environmental conditions are quite different from here. Several studies compare types of intensive grazing, such as Management Intensive Grazing or multi-paddock grazing, with arable cropland (Machmuller et al. 2015; Shawver et al. 2021; Trimarco et al. 2023). As a result, their findings reflect not only the effects of grazing management but also the impact of shifting land use from cropland to grassland. The UK study by Trickett and Warner (2022) compares grazed and ungrazed ley phases, so also can't be used to build the evidence base for mob grazing specifically. Both Mosier et al. (2021) and Teague et al. (2011) compare continuous grazing with multi-paddock systems and report improvements in various soil health parameters. Mosier et al. (2021) found not only higher total carbon stocks but also higher proportions of carbon in the stable mineral-associated fraction in the AMP system. However, in both of these studies it is not clear if the tall grass and frequent movements of livestock is necessary to result in these improvements, since there are no comparisons with less intensive rotational grazing systems. The study by Díaz de Otálora et al. (2021) is more useful since it compares two rotational grazing systems, one of which is "regenerative". They found increases in soil C in regenerative grazing systems, but no other indicators of soil health differed between the two grazing management approaches. While this finding is valuable, the environmental conditions in northern Spain differ significantly from those in the UK, which may limit the direct applicability of the results to UK contexts.

In the UK there have also been several projects recently that studied mob grazing (e.g. SEEGSLIP(15), Mob grazing: Impacts, benefits and trade-offs(16), Rothamsted cell grazing(17), Harper Adams review of mob or holistic grazing(18)). Some of these have included literature reviews, but none of these are publicly available yet. The Rothamsted cell grazing interim project report has recently been published. This project compares cell grazing (using TechnoGrazingTM infrastructure where animals were moved every 1-2 days to new pasture with the area allocated varied to suit desired recovery periods) and set stocking at the North Wyke research farm in West Devon. The project found increases in soil carbon contents due to cell grazing and no differences in compaction between the two systems.

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

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

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

16. https://farmpep.net/project/mob-grazing-defra-project

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

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

Table 1 Rapid summary of outcomes from peer-reviewed literature on mob grazing or related systems

Study type	Systems compared	Study location	Parameters measured	Outcome	Authors
Experiment	Conventional rotational grazing (6-10 d grazing, 15 d rest) vs Regenerative rotational grazing (1-2 d grazing, 24 d rest)	Northern Spain	Topsoil organic carbon, six enzymes (β-glucosidase, β-glucosaminidase, sulfatase, acid phosphatase, L-alanine aminopeptidase, and L-leucine aminopeptidase), simplified water retention index, biodiversity via 16S rRNA metabarcoding of soil prokaryotes.	Topsoil carbon significantly higher in regenerative system, no other parameters differed between the two systems	De Otalora et al, 2021
Field survey	Chronosequence of three sites following conversion to management intensive grazing from intensive arable system	Georgia, USA	Carbon stocks in top 30 cm of soil, cation exchange capacity (CEC), water holding capacity (WHC)	Clear increase in carbon stocks (75% increase over the starting value of 0.5% C) in first six years; plateau in carbon after 6.5 years; increased CEC by 95% and WHC by 35%	Machmuller et al. 2015
Field survey	“over-the-fence” study comparing adaptive multi-paddock grazing (AMP; rest:grazed day ratio >40) vs conventional grazing	Kentucky & Mississippi, USA	Organic carbon and nitrogen stocks to 1 m, dissolved organic matter (DOM), light particulate organic matter (LPOM), heavy particulate organic matter, (HPOM) mineral associated organic matter (MAOM)	13% more organic carbon and 8% more total nitrogen stocks to 1 m on AMP grazing fields; 25% more C in the MAOM fraction and 15% more C in the HPOM fraction for AMP grazing fields	Mosier et al 2021
Field survey	Monitored soil health over time (2 years; 2017, 2018) in a field converted from cropland to irrigated Management Intensive Grazing (MiG)	Colorado, USA	Bulk density (BD), water-stable aggregates, soil organic C (SOC), microbial biomass C, potentially mineralizable N (PMN), and β-glucosidase (BG) activity, pH, EC, plant-available K and P; 0-5 cm and 5-15 cm depths	Significant increase over time for: BG, MBC, PMN, pH, K; significant increase (negative effect) over time for BD and decrease for P	Shawver et al. 2021
Field survey	Follow-up study to Shawver et al. (2021) Monitored soil health over time (2 years; 2021, 2022) in a field converted from cropland to irrigated Management Intensive Grazing (MiG)	Colorado, USA	Bulk density (BD), water-stable aggregates, soil organic C (SOC), microbial biomass C, potentially mineralizable N (PMN), and β-glucosidase (BG) activity, pH, EC, plant-available K and P; 0-5 cm and 5-15 cm depths	Increase in BD over time; improved aggregate stability; increases in BG activity, MBC, SOC, general increase in soil biological and chemical health index,	Trimarco et al 2023
Field survey	Compared light continuous grazing (LC; n = 3); heavy continuous grazing (HC; n = 3); and planned multi-paddock rotational grazing (MP; n = 3) management	Texas, USA	Bulk density, resistance to penetration, aggregate stability, hydraulic conductivity, water infiltration, nitrate, ammonium, total N, organic matter, soil food web analysis (total & active bacteria and fungi, AMF infection, nematodes, protozoa, fungal:bacteria (F:B) ratio	Aggregate stability, resistance to penetration better with MP vs HC; Higher SOM, CEC MP vs HC; higher F:B ratio in MP vs HC	Teague et al. 2011
Field survey	Mob grazing a three-year grass-clover ley vs ungrazed three-year grass-clover ley	Hertfordshire, UK	Earthworm counts, soil organic matter	Higher earthworm counts in mob grazing compared to ungrazed, particularly the juveniles and endogeic species	Trickett & Warner 2022

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

4.4 Impacts of biostimulants on (plant and) soil health

Biostimulants are a broad category of crop inputs that can be defined as products that stimulate plant nutrition processes independently of the product's nutrient content with the aim of improving one or more of the following characteristics: nutrient efficiency, tolerance to abiotic stress, and/or quality (Storer and Berdini 2022). They can be broadly divided into non-microbial (e.g. seaweed extracts, humic substances, chitin and chitosan derivatives) and microbial (e.g. plant growth promoting rhizobacteria AKA PGPR, arbuscular mycorrhizal fungi AKA AMF) products. Biostimulants have attracted a lot of interest among the regen ag community as alternatives to fertilisers or pesticide. There are a wide number of commercial products currently on the market in the UK and many regenerative farmers are also producing their own biostimulants on-farm (e.g. compost teas, compost extracts, plant ferments). In 2016 the AHDB commissioned a review of the function, efficacy and value of biostimulant products available for UK cereals and oilseeds (Storer et al. 2016). In 2022 a further review on biostimulants was commissioned by Defra (Storer and Berdini 2022). These two documents comprehensively review the evidence base for commercially available products and make some recommendations. Storer and Berdeni (2022) identified 12 categories of biostimulant with new peer-reviewed evidence available since 2016. These included: Seaweed extracts (28 studies), Nitrophenol based (10), Humic acids (9), Fulvic acids (7), Amino acids (5), Mixtures (5), Glutacetine (4), Plant growth promoting bacterial (3), Synthetics of chemicals (2), Protein hydrolysates (2), Microalgae (1), Cyanobacteria (1). Their REA found evidence that 8 of the 12 biostimulant products can benefit arable and field grown horticultural crops, primarily in terms of growth or yield. The strongest positive effects were for amino acids, seaweed extracts, humic and fulvic acids (mixed) and nitrophenol based biostimulants. For other products results were either mixed (both positive and negative results reported) or the evidence was not from field studies (tested mainly in controlled environments) and therefore was not deemed as strong. Recommendations for future research and development priorities from this report were:

1. Conduct more testing of biostimulant efficacy under field conditions
2. Develop a standardised method of defining and measuring nutrient uptake, nutrient use efficiency and tolerance to abiotic stresses.

3. Provide end users with specific guidelines about how best to target biostimulant products
4. Investigate the evidence for economic benefit of biostimulant use.
5. Explore impacts of biostimulants on crop disease or pest tolerance/safety and if any products have any other additional effects outside those reviewed in the REA(19)
6. Build the evidence base on human and environmental safety of the biostimulants

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

Alongside the growing interest in commercial biostimulant products, many farmers are experimenting with producing biostimulants on their own farms through various methods for producing compost teas (both aerated and non-aerated mixtures of compost fermented with water and filtered Litterick et al.2004), compost extracts (filtered products of compost mixed with any solvent, but not fermented Litterick et al 2004), and/or seed treatments (e.g. controlled microbial compost seed dressings). A review was conducted about 20 years ago by UK-based scientists to evaluate the evidence for a range of organic products, including compost extracts and teas (Litterick et al. 2004). They reported some suppression of plant diseases by compost teas applied in the glasshouse and in field grown edible and ornamental crops. This benefit of compost teas has also been reported in more recent reviews (e.g.Sharma et al. 2024). Competition and disease suppression Curadelli et al. (2023) by microorganisms present in the teas has been proposed as the mechanism for disease suppression, as well as induced resistance and antibiosis(20).

Recent interest in compost teas among the farming community has grown out of interest in soil microbial conditions and particularly fungal and bacterial communities. Passive aeration methods popularised by Dr. David Johnson and Hui-Chun Su at New Mexico State University. The Johnson-Su system is designed to produce a compost with a relatively high population of fungal organisms. This compost is used to make a

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

20. Production of antibiotics or toxic compounds that inhibit or kill competing microbial species.

fungal-rich tea for application to the soil with the goal of shifting the soil microbial community towards a more “fungal-dominant” community. Many regenerative farmers subscribe to the theory that fungal dominant soils are important for maintenance of soil health and crop productivity (e.g. as advocated by Dr. Elaine Ingham(21)); the evidence and research needs linked to this are discussed in more detail throughout this Challenge section on soil health.

The Soil Association ran an Innovative Farmers Field Lab on compost teas in 2017/2018 and results were inconclusive with increased yields in some cases but no measurable changes in soil microbial communities due to the addition of compost tea(22). More recently Curadelli et al. (2023) conducted a meta-analysis on the evidence for yield promotion from compost teas; they found a slight yield benefit from added compost teas relative to a water control in 8 observation pairs, but negative effects from the very small sample set where compost tea was compared to conventional fertilisers.

O’Neill and Ramos-Abensur (2022) provide a detailed review of liquid ferments used in the Andes which bear some similarities to the homemade biostimulants used in the UK. Farmers in the Andes make liquid ferments using manure as the main component, but vary widely in terms of additional ingredients, such as molasses, rock dust, urine, wood ash, guano, plant biomass, and various minerals and salts, prepared in simple containers. Manure fermentation may be combined with locally sourced microbial inoculants, or with mineral preparations similar to those prescribed for more conventional foliar fertilizers. Many fermented liquid fertilisers also have added “effective microorganisms” or EM(23) which were developed in Asia for use in anaerobic methods of compost production (i.e. Bokashi). Much of the lore around the benefits of liquid ferments (including compost teas) attributes any plant growth promotion to their microbial properties, but the review by O’Neill and Ramos-Abensur (2022) could not find any evidence that demonstrated a positive impact on plant growth due specifically to microbes found in manure-based ferments that was clearly distinct from the effect of added plant nutrients in ferments. Or to put it more simply: benefits from manure-based ferments appear to be due to the nutrients they supply, not the added microorganisms.

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21. https://www.soilfoodweb.com/
22. Reports available here: https://innovativefarmers.org/field-labs/compost-teas-in-arable-cropping-2nd-trial/
23. To add to the complexity of systems and terminology, these are sometimes referred to as “efficient microorganisms”, e.g. as in the paper by Singh et al. 2011

Future research testing the efficacy of liquid ferments, compost teas, etc, should include treatments that provide similar concentrations of nutrients without the microorganisms present to verify the reasons for any observed plant growth promotion.

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

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

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

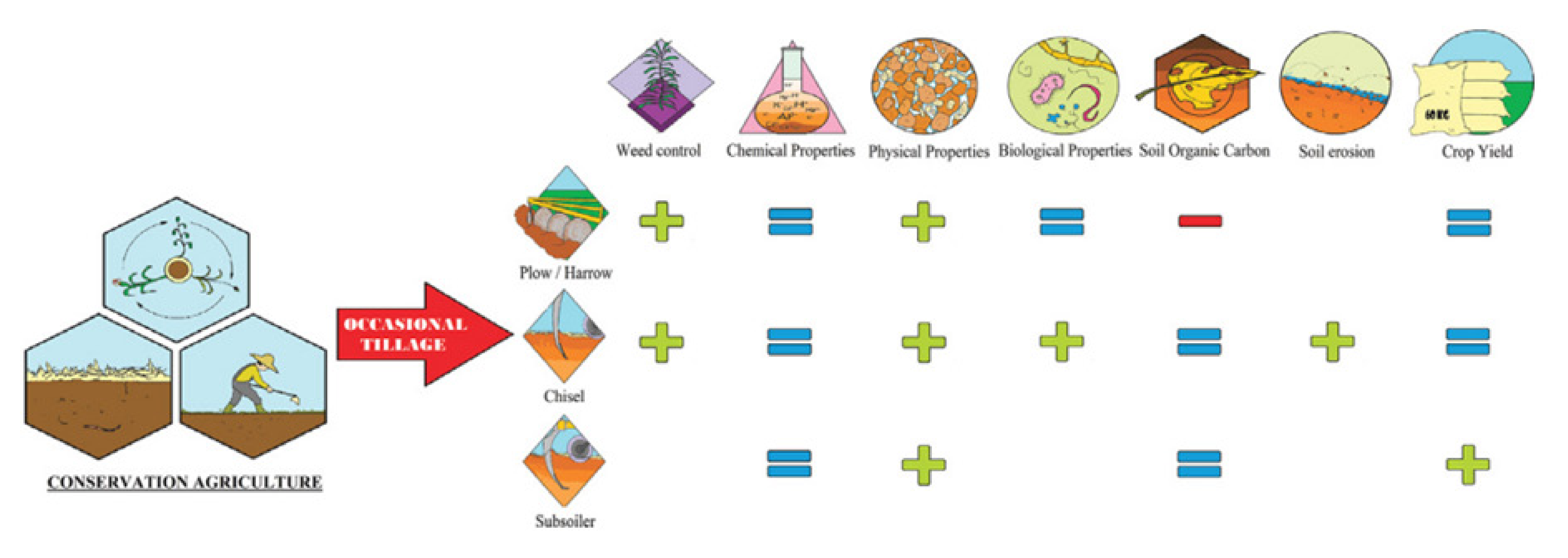
Minimising soil disturbance, often interpreted as no tillage at all, is one of the key principles of regenerative agriculture. But there remain questions about the long-term impacts of this practice on soil health, the environment, and agronomic productivity; no-till practices can lead to soil compaction,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

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

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

“Strategic” or “occasional” tillage is one area that has not been studied extensively under UK conditions. There have been about 100 papers published that use these terms; about a third of these are from Australia, with only one UK publication. Peixoto et al. (2020) published a useful global meta-analysis on this topic in 2020. They selected papers that did not use “rotational tillage” i.e. regularly scheduled tillage events, but instead focused on studies that used tillage to address a specific problem, most often soil compaction, but sometimes weed control or incorporation of residues. Figure 3 summarises the key messages from the paper and shows that impacts of occasional tillage on most variables were positive or neutral, with the only negative effect on soil carbon for plough/harrow interventions. This suggests that occasional tillage can be used with minimal negative effects, but there have been no systematic studies on this in the UK; more research is needed to confirm how strategic tillage could be implemented to address some challenges i.e. with weeds and compaction, while minimising negative impacts on soil health and C sequestration.

Figure 3 Graphical abstract from Peixoto et al (2020) showing positive (+), negative (-) and no (=) effects of three tillage methods on weeds, soil properties and crop yields



	Weed control	Chemical Properties	Physical Properties	Biological Properties	Soil Organic Carbon	Soil erosion	Crop Yield
Plow / Harrow	+	=	+	=	-		=
Chisel	+	=	+	+	=	+	=
Subsoiler		=	+		=		+

In addition to peer-reviewed studies, Defra has funded various studies over the years that have included tillage practices (Table 2). There are also various ongoing trials where tillage system is a factor (Table 3). It is therefore important to build on the existing knowledge and not duplicate existing projects and experiments when designing new studies on this topic.

Table 2 Some historic Defra projects that included tillage practices under UK conditions

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

Table 3 Summary of ongoing projects studying strategies to reduce tillage intensity in arable systems in the UK

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

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

A Web of Science search using the search terms ("soil biology" OR "soil health" OR "soil fungi" OR "soil bacteria" OR "soil biodiversity") AND (glyphosate" OR "Round-Up") in the topic field identified 143 peer-reviewed articles on the topic as of October 2024. These include laboratory, greenhouse and field studies using a range of application rates and frequencies and assessing effects on microflora (fungi, bacteria), soil fauna, and general microbial biomass and respiration. Conducting a review of this evidence base is beyond the scope of this review, but the meta-analysis by Nguyen et al. (2016) is a useful summary of many studies. These include field and laboratory experiments with treatments designed to replicate farm practice (dose rates <10 mg a.i./kg soil) as well as others designed to determine effect endpoints for ecotoxicology purposes (>100 mg a.i./kg soil). A quick survey of farmers on X (26 Oct 2024) returned typical application rates of 700-1000 g a.i./ha which translates to <2 mg a.i./kg soil using the assumptions in the paper. Figure 4 shows that in this meta-analysis rates typical for UK arable farmers had no effect on soil microbial respiration or biomass, both of which are useful indicators of general soil biological health. The meta-analysis concludes by stating that “generalisations about the toxicity or safety of glyphosate to SMR (soil microbial respiration) and SMB (soil microbial biomass) should be qualified with details of the conditions under which glyphosate is applied”.

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

Figure 4 Figure extracted from Nguyen et al. (2019) illustrating the effects of glyphosate on soil microbial respiration (SMR) and soil microbial biomass (SMB) at different rates of glyphosate application. Results of a meta-analysis including field and pot trials.

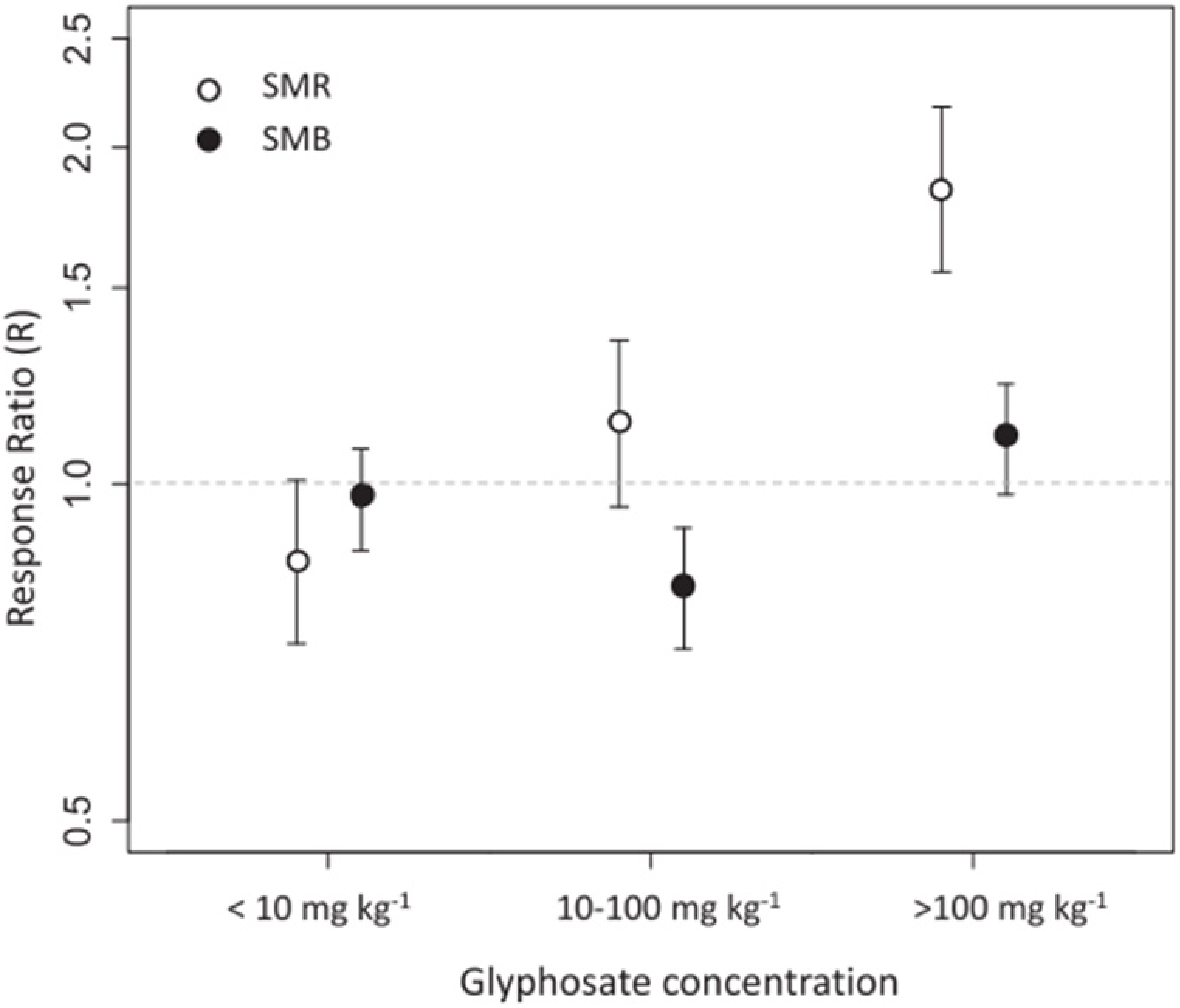


Fig. 3. The impact of glyphosate concentration categories on soil microbial respiration (SMR, open circles) and soil microbial biomass (SMB, filled circles). Error bars represent 95% confidence levels. The dashed horizontal line represents the no effect level. Values above the horizontal line demonstrate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

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

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

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

Organic and conventional systems (1 vs 2 in Table 4) are frequently compared using survey and experimental approaches. These comparisons are often done to assess differences in yields (Seufert et al. 2012; Ponisio et al. 2015). Impacts on soil health have been reported particularly using the DOK trial in Switzerland which compares biodynamic, organic and conventional systems of farming (Fließbach et al. 2007; Esperschütz et al. 2007; Joergensen et al. 2010; Mayer et al. 2022; Krause et al. 2022). In the UK, the Nafferton Factorial Comparisons Trials (also known as "QLIF") compare organic and conventional production systems. More recently a tillage treatment has been included as an experimental factor (Orr et al. 2011, 2012). Gattinger et al. (2012) conducted a meta-analysis to assess differences in soil C between organic and conventional systems.

Studies comparing the effects of tillage in organic systems only (1 vs 3 in Table 4) are not common, but this was the focus of the TILMAN-ORG(24) project which the Organic Research Centre and Newcastle University in the UK delivered in collaboration with European partners. As part of the TILMAN-ORG project Cooper et al. (2016) conducted a meta-analysis on the effects of reduced tillage intensity on crop yields in organic systems; they concluded that shallow non-inversion tillage minimised yield reductions while still preserving positive effects on soil carbon.

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

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

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

There are lingering questions regarding the long-term effects of reduced tillage intensity on soil health, the environment, and agronomic productivity. This issue was highlighted and added to the list of challenges at the workshop. While periodic cultivation can address some of these concerns, it remains unclear how this

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24. https://www.tilman-org.net/tilman-org-home-news.htm

occasional "strategic" tillage impacts ecosystem health and crop production. Additionally, the environmental impacts of strategic tillage compared with the use of glyphosate for weed control are poorly understood (a key question raised by Andy Cato and Andy Neal at the Future of Agriculture conference). This is a high-priority area for applied research. The focus should be to explore the impacts of no-till systems with glyphosate compared with systems using no glyphosate but with occasional/strategic tillage (including more intensively tilled organic systems) across the breadth of agronomic and environmental indicators. This research will provide better guidance on the most effective ways to implement regenerative agriculture practices in the UK environment.

Project Summary

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

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

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

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

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

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

Wider system impacts of regenerative agriculture need to be better documented to demonstrate the benefits of these practices. Impacts particularly on the water cycle (both flood risk and drought resilience; 5.1) need to be studied and understood. In addition, the net effects on greenhouse gas emissions are not known. Integrating legumes into rotations (5.2) can have a range of knock-on effects on emissions in the field and beyond the farm gate. A slightly broader statement on the wider impacts of regenerative agriculture on the environment also ranked highly (5.3 Practice and options to be assessed in terms of wider impacts), but it should be noted that there have been many papers published globally on environmental impacts of regenerative agriculture which should be reviewed before designing UK studies; various projects are ongoing that will also address these topics in the UK.
There is a perception that more crop breeding efforts should be targeted at traits important for regenerative farming. Variety evaluation and breeding for low N and pesticide inputs (3.3) was a high priority among workshop participants and has also been identified as important to levy payers in the recent AHDB Recommended List review process. Variety evaluation and breeding for weed competitiveness (3.4) and performance in reduced tillage systems (3.5) emerged as important topics at the workshop. These topics have been covered in peer-reviewed studies, but there have been few projects in the UK.

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

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

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

Authors' Recommendations

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

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

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

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

Appendix A

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

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

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