UK Research and Innovation

Multifunctional Metrics: Examining Circular Practices at the Farm Level

Charlotte Wheeler, AFN Network+ Champion

About the AFN Network+

The AFN Network+ (UKRI Agri-food for Net Zero Network+) is a unique network of 3,100+ academics, researchers, third sector organisations, policy makers, and agri-food industry professionals from farmers to retailers.

Together, we are working to identify key research gaps that may be holding the UK food system back from transitioning towards a net zero UK by 2050, while also enhancing biodiversity and healthy ecosystems, nurturing livelihoods, supporting healthy consumer habits, and minimising the environmental impacts of overseas trade. Our findings will inform the next decade of research investments in this area by UKRI (our funder and the UK research councils umbrella organisation).

Alongside our core research, we run in-person and online events, produce topical resources, and give out hundreds of thousands of pounds of funding a year.

The AFN Network+ is coordinated by the University of East Anglia, University of the West of England, University of York, and University of Leeds, and is a £5m, 3-year project funded by four research councils; the Biotechnology and Biological Sciences Research Council, Economic and Social Research Council, Engineering and Physical Sciences Research Council, and the Natural Environment Research Council.

Website: **www.agrifood4netzero.net/**

Email: **contact@agrifood4netzero.net**

LinkedIn: **www.linkedin.com/company/agrifood4netzero/**

X/Twitter: **@AFNnetwork**

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Introduction

The need for change in the food system is clear, yet the path forward must balance environmental restoration with the practical realities of farm economics and food production. The circular practices outlined in this document are some of the promising approaches that demonstrate potential for delivering co-benefits across multiple sustainability criteria, as outlined in Part 1 (*Multifunctional Metrics: Rethinking sustainability in food systems*). Crop–livestock integration, agroforestry, and low-input livestock systems on diverse swards offer the opportunity to increase circularity at the farm level, enhancing ecological resilience, storing carbon, supporting biodiversity, and creating farm enterprises that are more adaptable to the impacts of anthropogenic climate change.

These practices are evaluated through a framework that considers farm economics, climate change adaptation and mitigation potential, biodiversity impact, and circular economy principles. Each practice is assessed for their environmental credentials, but also for their capacity to contribute to viable, regenerative farming systems that can support both rural livelihoods and the broader public need for resilient and sustainable food production.

While not the only path to a resilient and sustainable food future, circular and low-input practices are currently underemphasized in both policy and research. Given the resulting lack of investment in their development and adoption, it is crucial that these practices receive greater attention. Food system policy must better recognise and embed the relationship between effective ecosystem functioning and food system resilience[1][2]. Business as usual approaches only entrench existing vulnerabilities, inequalities, and harmful impacts.

The transition to more sustainable and equitable food systems requires coordinated action that cuts across departmental and disciplinary silos. It requires a reorientation that centres the kinds of public goods our food system is capable of delivering; one in which equity, biodiversity, and resilience are foundational, rather than optional add-ons. This requires new ways of evaluating impact, and a shift in mindset. It requires diversification at multiple scales; including at the farm level, but also in terms of supply chains, and the kinds of foods we eat.

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Crop–Livestock Integration

Summary

Agriculture in the UK has become increasingly specialised over the past century, driven by government policy and support. This has been facilitated in part by the widespread utilisation of synthetic fertilisers which have allowed the decoupling of livestock from their historic role of cycling fertility in arable systems. While it is not necessarily desirable nor realistic to advocate for universal reintegration of crop and livestock systems, there is potential for significant benefits to be delivered through greater adoption of this practice, whether at a farm or regional level. Defra analysis suggests that arable soils in the UK have lost 40-60% of their organic matter, representing lost fertility, water storage capacity, and carbon stocks, as well as pollution[3]. Meanwhile, crops for animal feed account for 80% of nitrogen use in Europe[4] and it is estimated that the production of each tonne of nitrogen fertiliser equates to up to 10 tonnes of actual emissions, if including those associated with production and waste[5]. Precision fertilisation, and switching to renewables for fertiliser production therefore carry significant opportunities to help the sector decarbonise. Even so, plant uptake of fertilisers is limited in many arable areas by poor soil health; in some cases, use efficiency can be as low as 33%, meaning that 67% of nitrogen applied is lost to the atmosphere as nitrous oxide, or into groundwater[6]. This waste must be remedied if productivity and efficiency gains are to be realised, and emissions reduced. The degraded condition of many arable soils means they carry the greatest capacity for carbon storage, and introducing livestock into crop rotations can facilitate this by increasing soil organic matter levels. If managed correctly, doing so improves soil health and structure, water holding capacity, and therefore the overall resilience of cropland[7]. While avoiding overconsumption of animal-sourced proteins is crucial to limit greenhouse gas emissions and nutrient losses, livestock play a key role in future circular food systems, whether on land that is unsuitable or undesirable for crops (due to productive capacity or greater biodiversity value when intact), or by upcycling waste streams.

Climate Change Adaptation, Mitigation, and Net Zero

Integrated Crop-Livestock Systems refers to the practice of incorporating livestock into some stage of a crop rotation, such as when grazing cattle in an arable cover crop or grass ley. Integrated crop-livestock systems can address multiple environmental challenges whilst maintaining productive capacity. Crop-Livestock Integration was one of three recommendations for climate mitigation in the livestock sector made by the Food and Agriculture Organisation's (FAO)[8].

In Integrated Crop–Livestock Systems, livestock (typically considered the most land and resource intensive form of food production) have a particular opportunity to not only mitigate harm, but actively contribute to the delivery of multiple outcomes beyond food production, including nutrient cycling in cropping systems, soil health, and biodiversity. If managed in line with these goals, livestock can improve soil health through the cycling of nutrients and improving biological activity and soil structure[9]. This makes land more able to absorb large quantities of water, increasing resilience to periods of heavy rainfall, and simultaneously during drought conditions. In addition, more complex landscapes with a variety of habitats can help stabilise ecosystems and biodiversity over time, particularly in extreme weather conditions[10].

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It is notoriously difficult to model soil carbon storage potential, due to the huge range of variables at play, including soil types (there are over 700 in the UK[11]), management practices, and environmental conditions. Regardless, improved soil health is critical for the stability and resilience of our food system and should be supported[12]. UK arable soils are predicted to have lost between 40 and 60% of their organic carbon, and the wider cost of soil degradation in the UK is estimated to cost approximately £1.2 billion per year[13]. This represents a direct loss in fertility and productive capacity, as well as diminished food security and resilience, and downstream pollution. However, degraded soils have the greatest potential for carbon storage, and given the food security risk posed by continuing to deplete our agricultural soils, it is incumbent on us to use all available techniques to improve soil health.

The integration of livestock into crop rotations can deliver measurable improvements in soil health[14]. In comparison to synthetic fertilisers, livestock manure can not only provide a natural nutritional boost to depleted soils but improve soil structure and biological functioning, which has benefits for the resilience of agricultural areas to drought and heavy rainfall[15]. Healthy soils are able to absorb greater volumes of water more quickly, and retain water over dry periods[16]. They are also less prone to erosion due to improved soil structure and aggregate stability, and biological functioning[17]. While the application of farmyard manure to arable fields is often considered a proxy for truly integrated systems, the impacts of this kind of management are not like-for-like. Applying farmyard manure to arable fields represents the movement of carbon across different parts of the food system, while the addition of growing plants as found in leys in an arable rotation represents the legitimate transfer of atmospheric carbon into soil carbon stocks[18]. Compared to bare earth, cover crops and leys provide a temperature buffer for the soil in both hot and cold weather, which can extend the growing season and maintain biological functioning in more extreme temperatures[19].

Circularity

Low-input practices in arable systems can include diversifying crop production, implementing longer rotations including cover crops, intercropping and crop-livestock integration. These practices can reduce dependence on chemical inputs such as fertilisers and biocides, helping reduce the build up and resistance of crop pests and diseases[20], with the added potential for increasing environmental and financial resilience.

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Integrated crop-livestock systems in particular, carry potential for circularity. In contrast to linear systems that require the production (and waste) of inputs, integrated crop-livestock systems feature closed nutrient loops, enabling greater circularity at a farm and regional level[21]. Research in a European context emphasises the capacity of integrated systems to reduce external input dependencies whilst maintaining productivity levels. If well-implemented, livestock manure application in integrated systems can substantially reduce synthetic fertiliser requirements, with one study finding a reduction in nitrogen fertiliser requirements of between 50 and 90%[22].

Livestock integration valorises crop residues and by-products that would otherwise represent waste, converting these materials into valuable protein whilst simultaneously cycling nutrients back into cropping systems through manure deposition[23-24]. Crop residues serve multiple functions within integrated systems, such as providing livestock feed, building soil organic matter, and reducing erosion risk[25]. Work by Wageningen found that default livestock (those reared exclusively on waste-, by-, or co-products, or on cover crops and pasture) was more efficient from a land-use perspective than animal-free diets, due predominantly to the utilisation of these otherwise unproductive resources[26]. Because they reuse resources internally and rely less on external, fossil fuel–based inputs, integrated crop-livestock systems display a reduced "Environmental Load" (defined as the proportion of non-renewable energy invested into a system, compared to its output) due to a reduced need for non-renewable energy[27].

While manure can be applied to arable lands from separate livestock systems, there are added benefits of grazing in terms of weed and disease reduction and biological functioning[28], as well as "home" benefits of microbes from the system being recycled back into the same system. Livestock grazing of cover crops and crop residues enhances the biological processing of organic matter, accelerating nutrient release and improving availability for subsequent crop growth[29].

Biodiversity

Mixed farming systems have the capability to create greater habitat diversity compared to specialised systems by increasing landscape and temporal heterogeneity. The combination of cropping areas, grasslands, and transitional zones provides essential nesting, feeding, and overwintering habitats for numerous species groups, including ground-nesting birds, beneficial insects, and small mammals, many of which coevolved with these kinds of diverse and low-input landscapes. The temporal variation introduced through rotational grazing and crop rotations can also enhance habitat availability across seasonal cycles. Diversity in cover crops has been correlated to increased presence of beneficial insects that are predatory to crop pests[30]. Although plant diversity is a major factor influencing pollinator abundance and diversity, it is not inherently higher in mixed farming systems (which can still be intensively managed); equally, specialised systems may be managed in ways that support botanical diversity.

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Low-intensity agricultural systems provide critical buffer between more intensively managed or populated landscapes and protected areas, allowing for connectivity between sites[31] and providing the landscape heterogeneity that is the prerequisite for biodiversity[32]. Research suggests that mixed farms support significantly higher bird species richness compared to specialised arable or livestock enterprises[33], with particular benefits for farmland specialists species that have experienced population declines under intensive management[34-35].

Organic practices similarly tend to facilitate greater invertebrate abundance through the avoidance of insecticides. The potential benefits of livestock manure for many invertebrate species (and therefore the wider food web) is negatively impacted by the presence of parasiticides such as ivermectin[36]. This suggests that crop-livestock integration should incorporate principles of diversity (in terms of increasing the number of crop varieties in rotation, combination cropping, intercropping, or the use of green manures, leys, or wildflower strips) and reduce the use of pesticides (either directly applied to crops or through the use of treatments in grazing livestock) in order to fully realise potential benefits for biodiversity.

Other research suggests that integrating arable and semi-natural grassland can increase the presence of beneficial insects in arable areas[37]. Similarly, research from the Royal Society found that converting the least productive parts of arable areas to wildlife refugia lead to an increase in productivity in remaining areas; researchers found that removing the 8% least productive parts of their field edges from production maintained yields over the field scale through improved ecological services and better use of time and resources on productive areas. The study found that results were more pronounced over time[38].

Economics

At a basic level, reducing dependence on inputs can lead to a range of positive impacts; it reduces the likelihood of nutrient pollution in the local environment, as well as a farm business's variable costs, making them less vulnerable to fluctuations in the costs of these inputs on the global market[39].

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Integrating crop-livestock systems can reduce the risk profile of agricultural enterprises through diversification. It provides a buffer against climate variability, since livestock enterprises can maintain income streams during crop failures, and conversely, crop production can offset periods of livestock market volatility. This diversification proves particularly valuable under increasing weather unpredictability[40]. Significantly for climate adaptation, integrated systems demonstrate superior adaptive capacity compared to specialised enterprises. Farmers operating integrated systems can adjust the balance between crop and livestock enterprises in response to seasonal conditions, market signals, and climate forecasts[41] a valuable adaptation mechanism as climate variability intensifies across temperate regions.

While specialised systems where crops and livestock are managed independently demonstrate economies of scale, integrated systems can benefit from economies of scope, where shared labour, infrastructure, and machinery reduce the costs for each enterprise.

There is promising evidence that far from competing with the primary crop, the integration of livestock into cropping areas can improve the yield of the primary crop[42]. Further potential benefits are decreased livestock feed bills, reduced water requirements as a result of improved soil structure, and reduced demand for inputs such as fertilisers or pesticides[43]. However, benefits may accrue over time and not be apparent in the first year, requiring an up-front investment to transition to these alternative practices.

Future Research

Integrated crop-livestock systems can enhance resource efficiency, biodiversity, and landscape resilience, though their impact on emissions depends on system intensity and input efficiency[44]. The trend towards specialisation of agricultural systems over the past century has been reflective of the time; one of abundant fuel, affordable inputs, and global trade[45]. However, these systems are also highly dependent on these conditions, a vulnerability that is mitigated in integrated-crop livestock systems[46].

Short-term wins for policy could be the promotion of manure management and collaboration and knowledge exchange between arable and livestock farms. For example, through muck-for-straw deals or the use of “flying flocks” in which livestock farmers temporarily graze arable fields in an exchange of land and grazing for fertility. There is a need for greater support for farmers looking to diversify directly through livestock integration, in order to reduce synthetic fertilisers and feed demand[47]. Long-term strategies should encourage a greater diversity of farm types within regions, which requires strategic investment in processing infrastructure and logistics. Effective crop-livestock integration requires coordination between different farms, facilities for manure storage and transport in specialised systems; and livestock transporters, vets, abattoirs and markets in mixed systems[48]. These elements may be insufficient or lacking, limiting the feasibility of nutrient and resource cycling at scale.

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[48] ibid

Slurry from dairy systems is less easy to transport than farmyard manure due to its high water content. Whether it is more useful and sustainable to use it for anaerobic digestion locally, separate or dry it to enable transport to low-nutrient areas, or potentially adjust individual systems to produce farmyard manure instead of slurry, depends on both the individual farm and wider regional context.

Economic uncertainty is a further deterrent to adoption. While integrated systems may provide environmental and ecosystem service benefits, the short-term financial returns are often unclear or unpredictable[49]. Farmers, therefore, tend to be cautious about investing in new systems without guaranteed profitability or clear evidence of economic benefits.

To overcome these barriers, further piloting of cooperative models that allow crop and livestock farms to work together is needed, which allow for maintaining some economies of scale while enabling nutrient recycling and resource sharing[50]. Properly designed opportunities for knowledge exchange, demonstration farms, and technical support to reduce farmers' perceived risks and to showcase successful integration models in practice are all opportunities to increase uptake. There is also a need for regional planning approaches that align crop and livestock production zones to reduce transport distances and promote circular resource flows within local food systems[51].

Regarding future research, there is the need for more detailed economic assessments of integrated systems across different UK regions to better understand profitability and resilience compared to specialised farms. There is also a need for studies on supply chain and infrastructure models that can make nutrient recycling logistically and financially viable at a regional scale. Evaluations of policy impacts on integration uptake are needed to identify where current schemes succeed or fall short. Further, robust environmental data on outcomes such as soil health, nutrient leaching, carbon storage, and biodiversity under integrated systems would strengthen the evidence base. Lastly, there is a need for social research into farmers' decision-making processes, cooperative arrangements, and trust-building mechanisms that influence the adoption of integrated farming practices.

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[51] ibid

Adaptive Multi-Paddock Management in Low-input Multi-Species Swards

Grasslands cover approximately 40% of the UK and can contribute to a number of ecosystem services including clean water, air, erosion control and flood protection, pollination, food provision, and cultural services[52-53]. They not only encompass some of our most biodiverse and rare habitats, their carbon storage potential is strongly linked to management practices; despite this, they currently receive comparatively little emphasis in UK climate and nature recovery strategy with no dedicated delivery mechanism or leadership existing for grasslands[54]. While the UK Government's current environmental action plans provide extensive policy support and funding mechanisms for trees and peatlands (including dedicated resources, monitoring systems, and inclusion in national and international climate strategies), grasslands do not benefit from similar measures[55].

This is compounded by the fact that much of the historic research pertaining to grazing livestock and requirements in terms of land use or productivity fail to reflect real agricultural practices being undertaken by pioneering pastoral farmers. However, there are few, though increasing, studies investigating the impacts of more progressive grazing practices, some even within a UK context[56]. These are beginning to provide an evidence base for the anecdotal evidence experienced by farmers in the UK; and globally of what farmers have been experiencing through the adoption of these practices in recent decades, including grassland's ability to facilitate increased biodiversity, resilience to extreme weather, and grassland productivity, with reduced inputs.

Much of the historic research for extensive grazing systems has analysed set-stocked grazing (in which animals graze the same unit area for a prolonged period of time, including up to an entire growing season) or rotational grazing systems based on similar extended grazing periods. In contrast, Adaptive Multi-Paddock (AMP) grazing refers to a grazing management style based on the frequent rotation of livestock through temporary paddocks to facilitate a range of outcomes. These grazing periods range from moving every few hours, to a day, or three days (though ideally not much longer) and are followed by extended paddock recovery periods, which are dictated by conditions and management aims. Such management can deliver a range of outcomes; Graziers may manage their animals with the aim of maximising biodiversity, or to maximise beef production with minimal inputs, something between the two, or something else entirely. The adaptive term refers to the flexibility of the approach; beyond some principles and an understanding of animal behaviour and grassland ecology, it is a highly responsive and iterative practice that can adapt to unexpected changes. Other similar approaches are Holistic Planned Grazing (created by the controversial Alan Savoury) or mob grazing. Key innovators include Alan Savoury, Andre Voisin, Gabe Brown, and Greg Judy.

Climate Change Adaptation, Mitigation, and Net Zero

Dr Amanda Deakin, Science Lead at FAI Farms, ran a project in collaboration with McDonald's to investigate the impacts of transitioning from set-stocked to AMP grazing, with promising results after four years of monitoring[57]. The project found substantially improved water infiltration rates, enhanced resilience to drought and flooding and improved pasture productivity. Results from Trinity Ag Tech carbon sampling suggested that carbon storage in the permanent pasture outweighed emissions from the herd, resulting in a net carbon balance of -49.70 tCO2e over the course of the project. However, this figure may fluctuate and is likely to eventually reach a saturation point. The Farm Carbon Toolkit estimates that a 0.1% increase in soil organic matter can equate to 8.9 tonnes of carbon stored per hectare; given the poor quality of much of the UK's soils this suggests an opportunity for climate adaptation and mitigation, even if eventual saturation is assumed. Trinity Ag will conduct further analysis in 2027 and McDonald's is expanding the study to a further 11 farms.

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There is increasing recognition of the role that animal health and welfare play in the climate efficiency of livestock systems[58]. On the one hand, issues such as low-grade lameness or mastitis, which may be found in both extensive and intensive systems, may not be tackled as systematically as acute disease outbreaks, even though they increase emissions intensity of systems as animals are rendered less productive[59]. Estimates in the UK suggest that up to 30% of the national dairy herd may have some level of lameness, suggesting substantial opportunity for emissions savings[60]. Similarly, animals who are physiologically stressed, for example due to extreme weather, are less productive along a range of metrics[61]. One UN report found that parasite burden could lead to a 33% increase in emissions, and that increased adoption of animal health practices could reduce sector emissions by 18-33% alone[62]. Usefully, AMP and other grazing approaches based on longer rotations can reduce the need for anthelmintics in livestock, as they interrupt the life cycle of parasitic worms and reduce their exposure to contaminated ground. It is encouraging to see evidence supporting the widespread on-farm experience, which suggests that grazing management can be as effective as parasiticide use for reducing gastrointestinal parasites[63]. This has positive implications along multiple metrics beyond animal welfare and productivity, including mitigating the risk of anthelmintic resistance in parasite species, and facilitating improved soil health and biodiversity by reducing the need to use anthelmintics, which have harmful effects on soil microbiological[64] and insect communities, and so the wider food web[65].

Similarly, extending the productive lifespan of dairy cattle improves herd efficiency by reducing the number of non-productive animals (heifer replacements) in the herd, resulting in reduced emissions in comparable farms[66]. Highly intensive systems may see the reproductive lifespan of cows average at only three years out of a broader possible lifespan of 20, there is clearly opportunity for improvement[67]. Generally, where welfare improvements correspond with gains in productivity they can lead to a good return on investment[68] and reduced emissions[69].

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Circularity

Multi-species swards (in comparison to simpler one to two species mixes) present a range of benefits from an environmental and livestock performance perspective. The Toolbox of Multi-species Swards (TOMS) project researched the uses and benefits of multi-species swards. In a meta-analysis of 77 relevant studies, they found that diverse mixes had a higher dry matter yield, improved digestibility, and greater potential for reducing nitrogen leaching and weed control, as well as improved milk productivity in dairy cattle and weight gain in lambs. Control swards in the studies were typically a two-way mix of ryegrass and clover, while the diverse comparisons were generally a mix of three to five species. Roughly half of the studies compared cutting to grazing regimes. None of the grazing regimes in the studies were of adaptive multi-paddock grazing systems, which have been found to improve the productivity of swards[70], meaning the benefits described by the study may be conservative compared to their potential.

Species diversity in swards, or through the availability of tree browse from hedgerows or agroforestry systems (see Agroforestry), provides greater nutritional diversity[71], particularly of minerals and vitamins[72], improving performance and reducing the need for mineral inputs for livestock[73]. Indeed, the presence of tannin rich species in pasture can provide an antiparasitic effect, which, combined with managed grazing, can greatly reduce the need for anthelmintic treatments in livestock. By increasing the proportion of leguminous plants in the sward, low-input grazing systems can reduce or eliminate the need for synthetic fertiliser, while maintaining productivity.

Biodiversity

A significant predictor of the biodiversity potential of grassland is the degree to which it has been agriculturally "improved" by the addition of nitrogen-based fertilisers, or through regular ploughing and reseeding[74]. Improved grasslands tend to carry little biodiversity value, typically consisting of few species dominated by competitive grass species such as italian ryegrass. While true unimproved grasslands are now rare in the UK, they are highly biodiverse and valuable ecosystems in their own right. Semi-improved grasslands have had some level of intervention, characterise a much larger proportion of the UK, and carry restoration potential, if they are managed sympathetically and not further intensified[75].

Research on biodiversity benefits of low-input grazing in diverse swards demonstrates significant positive impacts across multiple taxonomic groups[76], though outcomes depend heavily on context including grazing intensity, timing, and sward composition. Long-term monitoring across upland grassland found that short-term studies often are unable to capture the impacts of changes in management, requiring longer-term monitoring to see results.

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Planned grazing can contribute to increased heterogeneity in rural landscapes[77], and is critical to the spread and on-going maintenance of many valuable habitats, such as heath, fen, marsh, floodplain, and wood pasture, without which they would no longer exist[78] and which in turn, support a range of invertebrate, bird, and mammalian species[79-80]. Studies show that livestock grazing can create essential microhabitat diversity through grazing patterns, with areas of short grass, taller tussocks, and disturbed ground supporting different species assemblages[81]. During the FAI Farm McDonald's project, bird recording data revealed a 23% and 34% increase in bird diversity compared to neighbouring farms, along with over 30 recorded pasture species[82]. This structural heterogeneity is crucial for maintaining high biodiversity in grassland systems, with a diversity of grazed habitats needed at a landscape scale to improve invertebrate diversity[83]. Conversely, the abandonment of grazing in diverse pastures can lead to the encroachment of scrub, simplifying the habitat and reducing species richness[84-85].

The UK Centre for Ecology and Hydrology ran a project called SEEGSLIP (Sustainable economic and ecological grazing systems - learning from innovative practitioners) which encompassed a range of studies and aimed "to evidence the practices of Pasture-fed Livestock Association (now known as Pasture for Life) producers and farmer members using holistic, system-based approaches." Pertinent findings included that increased pasture diversity was positively correlated with both soil invertebrate populations and soil nitrogen and carbon[86].

It is significant to note that many studies evaluating low vs high intensity grazing are incorrectly used as analogues for set-stocked vs Adaptive Multi Paddock systems. Many of these studies present a binary, presenting low stocking *rates* (a low number of livestock across the entire grazing platform, as found in many conservation grazing systems) as synonymous with low grazing intensity, and contrasting this with commercial set-stocked systems (which can impede the ability of pasture plants to set seed and reproduce, usually limiting species diversity), which is considered high grazing intensity. In contrast, more adaptive systems may be considered to be high intensity because a greater number of animals may be grazed over a smaller area (i.e. higher stocking *density*), however, crucially, they are moved onto new grazing frequently enough that pasture plants are able to recover and reproduce before the next grazing. This can deliver similar outcomes to the low intensity and low stocking rates of conservation grazing systems, despite higher numbers of animals and more "intensive" grazing.

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This understanding carries importance for analysing studies that evaluate the impacts of grazing. Studies such as those conducted by Hopkins and Holz in 2006 demonstrated that low-intensity cattle grazing in species-rich meadows maintained botanical diversity while higher stocking rates led to species loss and dominance by competitive grasses[87]. While this may be taken to suggest that the higher stocking *densities* of adaptive multi-paddock systems (i.e. the number of animals within a grazing cell) may deliver similar negative outcomes to the higher stocking *rates* (i.e. the number of animals over the grazing platform as a whole) in set stocked systems, in practice they may correlate better with the low-intensity conservation grazing systems. This is because the low stocking rate in conservation grazing, and the high stocking density but short time period of AMP grazing both provide the longer rest periods required for less-competitive pasture species to proliferate.

If we conclude that the effects of low-intensity grazing as described in many studies is the result of long rest periods rather than stocking rate, then we can draw cautious parallels with AMP grazing despite the current dearth of research into its impacts. Research suggests that extensively grazed pastures can contain more beetle species than intensive grasslands, with particular benefits for dung beetle communities that support nutrient cycling[88]. Similarly, research on the impacts of intensification for biodiversity across UK farmland demonstrated that mixed grazing systems with cattle and sheep at low stocking densities supported significantly higher densities of ground-nesting birds including lapwing, skylark, and meadow pipit compared to intensive grasslands[89]. Similar research has found that extensive grazing provided crucial invertebrate food sources for declining farmland bird species[90].

As seen with integrated crop-livestock systems, the key predictors of biodiversity are diversity of habitat conditions and low-inputs[91] , which are less compatible with intensified agricultural landscapes.

Economics

Rothamsted's 2024 comparison of AMP grazing compared to set-stocked grazing found that carrying capacity doubled on the managed grazing site compared to set-stocking[92]. This has important implications for, perhaps ironically, the role of grazing livestock in actually "releasing" land for other uses through substantial productivity gains. If combined with silvopasture, there is potential for even greater gains for biodiversity, carbon storage, animal welfare, and system resilience.

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Similarly the grazing management in the FAI Farm study allowed the cattle to be finished on a 100% pasture diet and outwintered, eliminating winter housing costs such as bedding and feed. Despite these lower inputs, the cattle were still able to reach slaughter weight under 24 months, indicating that the transition to AMP grazing did not negatively impact productivity[93]. The SEEGSLIP project noted that "whilst such systems in Great Britain are highly variable according to practitioner, location and practice, they are economically viable and deliver wide ranging public goods." Although low-input farmers may sell their products into a range of markets and so are not guaranteed a premium, reduced variable costs such as feed, winter housing, and veterinary bills contribute to healthier net profits. These cost savings and efficiencies highlight the potential economic advantages of this system.

Future Research

Grasslands already provide a suite of ecosystem services[94], and have a greater potential to provide a range of provisioning, regulating, and cultural benefits if their condition is improved. Adaptive management practices such as AMP grazing can be difficult to monitor due to variations in i) environmental context, ii) farm system, iii) practices between farmers, iv) length of time in an AMP system. Despite these challenges, further research is needed to identify the potential benefits and impacts of low-input adaptive grazing regimes along multiple metrics. This requires more holistic approaches towards evidence gathering. Possible avenues are demonstrated in tools such as the Global Farm Metric, or the Organic Research Centre's Public Goods Tool. Both of these evaluate farms along multiple economic, environmental, and social metrics including soil health, water use, diversity, manure management, and social capital.

It is critical to remember that the relative benefits and harms of a farm cannot be reliably predicted based on system type alone; recent research by Dr Harriet Bartlett found that high environmental and welfare outcomes on pig farms were possible across multiple system types, and outcomes were determined by management rather than membership of a particular category of farm[95]. This could suggest a need for evaluation methods based on outcomes, ideally along a suite of metrics, rather than simply switching production types from more extensive to intensive, or vice versa.

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Agroforestry

As a practice, agroforestry has perhaps the greatest potential to deliver benefits along metrics such as carbon sequestration, biodiversity recovery, and food system resilience simultaneously[96]. It warrants greater research and investment, given the political context of the UK government's tree planting targets, its commitment to net zero, commitment to 30% restoration of nature, and the ongoing debate regarding land use in the UK. Interestingly, while it is commonly viewed that incorporating trees will lead to a decline in the primary output of the land (for example arable crops) often in well-implemented agroforestry systems the opposite effect can be found; the microclimate, biodiversity, and soil health benefits of trees can improve the productivity the land, while a tree crop can deliver a second "crop" that didn't previously exist[97] . This is in addition to public good benefits such as carbon sequestration and biodiversity. However, care should be taken to ensure selected agroforestry species are compatible with desired outcomes to ensure the relationship between tree species and crop species is beneficial and not competitive.

Agroforestry systems are also more resilient to extremes in weather, providing shade and reducing fluctuations in temperature for crops and livestock, as well as increasing resilience by diversifying production[98]. As a result, agroforestry provides dual potential as both a climate change adaptation and mitigation strategy. These benefits are only likely to become more relevant as the extreme weather effects of climate change intensify over coming years. As a practice, it is applicable to arable, horticultural, and livestock systems.

They can also increase efficiency from a land-use perspective. A 2005 synthesis of silvoarable agroforestry systems across Europe found that integrated tree-crop systems achieve Land Equivalent Ratios of 1.2-1.4 compared to monocultures, meaning they displayed 1.2 to 1.4 times the productivity per unit of land area than if the two crops were grown separately[99].

Climate Change Adaptation, Mitigation, and Net Zero

The potential for well-planned agroforestry systems to contribute to the adaptive capacity of UK landscapes should be a key driver for their widespread uptake. Mosquera-Losada et al. (2018) examined agroforestry as a climate policy tool in Europe and found that these systems simultaneously address multiple policy objectives in line with the Sustainable Development Goals[100]. Their analysis found that agroforestry systems demonstrate better performance on sustainability indicators compared to conventional agriculture, achieving climate mitigation through carbon sequestration, adaptation through enhanced system resilience, rural development through diversified income streams, and environmental protection through circular resource management.

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The integration of trees into farmed landscapes can improve landscape's resilience to extreme weather. Studies have suggested that trees can reduce wind speed by up to 30 times the height of the treebelt, with benefits including reduced wind erosion and evapo-transpiration, and an extended growing season due to improved microclimate[101]. These effects can benefit livestock systems through improved welfare and therefore productivity of livestock who are less exposed to harsh conditions. Additionally, tree browse can serve as highly nutritious, mineral-rich sources of fodder for grazing livestock[102], particularly in drought conditions where pasture may be less reliable[103]. Rather than competing with pasture, at appropriate spacing, tree planting can improve pasture conditions through the creation of microclimates and improved soil structure. Interestingly, recent research found that cattle grazing on a mix of willow fodder and grass (WFG) produced 27% less methane daily compared to those grazing on perennial ryegrass alone (PRG), with no negative impact on performance[104].

In extreme wet weather, similar positive relationships are found. UK Environment Agency documented that land with riparian woodland and field-edge trees experienced reduced flood damage during the 2007 floods, compared to farms with minimal tree cover[105]. In regards to climate mitigation, agroforestry systems in the UK and across temperate Europe have demonstrated considerable potential for carbon sequestration. Numerous studies have quantified carbon accumulation in both soil and biomass across a range of temperate agroforestry systems, though rates vary depending on species composition, management practices, and system age. One meta-analysis indicated that soil organic carbon (SOC) accumulation may range from 0.21 to 0.36 tonnes of carbon per hectare per year in the top 40 cm of soil, equivalent to approximately 0.77 to 1.32 tonnes CO_2 per hectare annually[106]. Systems with hedgerows and tree belts tend to achieve higher rates, with long-term studies suggesting combined soil and biomass sequestration of between 2.1 and 5.2 tonnes of carbon per hectare per year, or 7.7 to 19 tonnes CO_2 annually[107]. In high-biomass silvoarable systems, such as poplar intercropping trials, total sequestration rates of up to 7 tonnes of carbon per hectare per year have been recorded, primarily through rapid tree growth and increased soil carbon inputs[108]. These findings are echoed in southern Europe, where a 2014 study found that Portuguese montado silvopastoral systems stored 40–60% more soil carbon than adjacent grasslands, with the most substantial accumulation occurring in the upper 20 cm of soil[109].

The positive impacts from tree planting tend not to be experienced until several years after trees are planted, meaning that land managers may experience delayed benefits. While results differ by context, the evidence consistently supports the role of agroforestry as a meaningful contributor to climate mitigation in temperate agricultural landscapes.

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The permanence and magnitude of these carbon benefits are reliant on long-term management and the accounting of land-use change effects. Graves et al. (2020) argue that silvopastoral systems may offer more durable carbon storage than short-rotation silvoarable systems, though both outperform conventional agriculture in terms of mitigation potential[110]. The Woodland Trust estimates that "*Establishing agroforestry on 10% of the UK arable area over 30 years (i.e.16,000 ha per year), and assuming a halving of arable GHG emissions per hectare, would enable the arable sector to reach net zero by 2050. Establishing agroforestry on 30% of UK grassland over 40 years (i.e. 3.35 million hectares; 84,000 ha per year), and assuming no other changes, would enable the livestock sector to reach net zero by 2050.*"[111] Although they bear further scrutiny, these figures underscore the strategic importance of combining tree planting with agricultural land in national decarbonisation efforts, particularly when integrated into broader land use and climate policy frameworks.

In terms of carbon storage, mature and more diverse agroforestry systems have been demonstrated to store more carbon aboveground than either crop monocultures or modelled tree plantations of single species[112]; however, as with all practices, implementation is key as poorly-managed agroforestry systems in one study were found to house lower total stocks than agricultural monocultures.

Circularity

Agroforestry systems facilitate a shift from linear models towards closed-loop systems that enhance both environmental sustainability and food system resilience. Rosenstock et al. (2016) identified how agroforestry addresses the three pillars of climate-smart agriculture (productivity, adaptation, mitigation) simultaneously through circular design principles. The productivity pillar is enhanced through complementary resource use and reduced input requirements; the adaptation pillar through diversified systems that create multiple feedback loops enhancing system stability; and the mitigation pillar through enhanced carbon sequestration and reduced greenhouse gas emissions from decreased fertilizer use[113].

Central to the circular economy concept is the principle of closing nutrient loops. Jose (2009) identified how trees in agroforestry systems function as biological pumps, accessing nutrients from deep soil layers and redistributing them through leaf litter and root turnover, making them available to shallow-rooted crops, mitigating the need for external inputs[114]. These circular nutrient processes are particularly effective in degraded lands, where agroforestry systems help restore soil fertility through continuous organic matter input and reduced soil disturbance[115]. If managed organically, they can support the proliferation of beneficial predatory insects, potentially reducing the need for pesticides[116].

Research from 2009 documented how agroforestry systems simultaneously deliver carbon sequestration, improved water quality through reduced runoff and nitrate leaching, enhanced biodiversity, and soil conservation through the reduction of erosion. These services are interconnected through circular processes where, for example, enhanced soil health supports greater biodiversity, which in turn improves pollination and pest control services, reducing reliance on external inputs[117].

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Biodiversity

While biodiversity recovery is necessary in all areas, agroforestry has emerged as a critical practice for enhancing biodiversity and strengthening the resilience of managed landscapes, including temperate food systems[118]. Its ecological contributions, particularly in the context of climate adaptation and ecosystem service provision, remain under-leveraged in mainstream agricultural policy. Well-designed agroforestry systems improve the diversity of agricultural systems, providing a greater range of habitat types, food sources, and connectivity for diverse and species-rich assemblages[119].

In temperate environments such as the UK, agroforestry has been shown to increase species richness across multiple taxa[120-121]. A meta-analysis by Torralba et al. (2016) synthesised 53 studies and found that agroforestry systems supported higher species richness than conventional monocultures, with particularly pronounced gains for birds, arthropods, and vascular plants[122]. Well designed silvoarable systems such as alley cropping can increase populations and diversity of beneficial species such as spiders[123] as well as for pollinators[124]. These outcomes are attributable to the structural heterogeneity introduced by tree-crop integration, which creates a mosaic of habitat types and ecological niches.

The integration of trees in agricultural areas can support soil microbiology[125] although research in this area, particularly deeper soil depths, remains underdeveloped. In many cases, agroforestry supports higher plant and butterfly richness than conventional agriculture and can more than double bird species richness[126]. These ecological benefits are not incidental, but integral to the resilience of food systems.

Economics

Studies demonstrate that there is potential for well-designed agroforestry systems to enhance farm profitability through diversified income streams, reduced input costs, improved productivity, and access to emerging markets for ecosystem services. However, these findings can be the reverse in poorly-implemented systems. This could be where tree spacing or species selection is incompatible with management or existing crops, or where subsidies or markets don't exist for tree products. There are often high initial establishment costs and longer payback periods, highlighting the need for subsidy support, and for technical advice to allow as short a window before financial benefits accrue[127]. There are also different implications for arable and pastoral systems.

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Agroforestry operations can experience lower income variability than specialised systems, with positive cash flows even during crop failure years. Nutrient cycling from tree litter and nitrogen fixation can reduce fertiliser costs, while a study of walnut agroforestry systems was economically profitable in both marginal and productive areas of the Midwestern United States.

Animal welfare and productivity benefits are also well-documented. Broiler chickens with access to trees exhibit more natural foraging behaviours, reduced fear, and improved markers of leg and foot health suggesting less time lying down, as is common in housed systems. In dairy cows, research finds that cows with access to tree shade showed reduced respiration rates and body temperatures during hot weather, with milk production maintained and improved by 3% in cattle with shade access. Research reported that sheep in tree-sheltered systems had half the lamb mortality compared to lambs in exposed areas during harsh weather. However, care should be taken to ensure silvopasture planning ensures adequate forage availability and does not outcompete pasture plants. Other research suggests sheltered livestock require less energy for thermoregulation, allowing better feed conversion as more nutrients are directed toward growth and production rather than maintaining body temperature[128].

Future Research

It is critical that agroforestry schemes are well designed for their context and desired outcomes, to avoid seeing negligible, or even negative results. Despite the growing body of evidence of agroforestry's potential ecological and economic benefits, its uptake in the UK remains limited, due to structural and operational barriers[129]. Recent research suggests that while economic and financial impacts dominate the list of factors influencing adoption, knowledge-based constraints are equally significant; qualitative research from the UK found that the most frequently cited barriers include a lack of conceptual, practical, and economic understanding of agroforestry, as well as limited access to case studies and demonstration farms[130]. This study found that along with knowledge-based factors, economic/financial factors made up nine of the top ten ranked factors incentivising/disincentivising farmers to adopt agroforestry. These included; "Lack of conceptual understanding and knowledge of agroforestry", followed by "Lack of practical understanding and knowledge of agroforestry", while "Lack of economic understanding of agroforestry" and "Access to case studies and demo farms" ranked equal third. "Lack of awareness of agroforestry among farmers" ranked fourth, and the potential for agroforestry to enable research ranked last. In a similar EU study, key barriers to the adoption of agroforestry practices were topped by conceptual and practical knowledge, followed by practicalities such as perceived complexity and management burden, as well as uncertainty of benefits[131]. Path dependency of current practices was facilitated by a lack of policy support for agroforestry practices.

This raises the question: does the knowledge needed for change not yet exist, or is it not available in a relevant form? The somewhat marginal position of agroforestry research suggests that the academic field itself may still be developing, particularly in temperate contexts[132].

This knowledge gap is compounded by a policy environment that has yet to fully integrate agroforestry into mainstream agricultural and environmental strategies. While European research has largely focused on agronomic and ecosystem service dimensions, it has often overlooked the social and economic co-benefits more commonly documented in the Global South.

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Future research should engage more deeply with the socioeconomic dimensions of agroforestry in temperate systems. New methods to increase agroforestry uptake should focus on peer-to-peer knowledge exchange, and promoting co-design and co-creative systems[133]. Some farmers report concerns regarding the flexibility of land-use after tree planting, or of decreasing the value of land. There is a pressing need for interdisciplinary studies that explore farmer decision-making, land tenure dynamics, and the role of peer influence in shaping land use practices.

The potential benefits of agroforestry in a UK context from an ecosystem services perspective is not currently well-modelled; given the UK government's tree planting targets and the need to reduce emissions in the livestock sector, it seems highly relevant to better understand the potential benefits and impacts that greater integration of trees into arable and grassland systems may have on farm-level emissions.

Ultimately, increasing the uptake and success of agroforestry in the UK will depend on a dual investment: in the generation of knowledge that is socially and economically meaningful, and in the creation of policy environments that are capable of recognising and rewarding multifunctionality (see Report 1). The land equivalent ratio, a common metric for assessing productivity, still fails to capture the non-market values generated by agroforestry, such as biodiversity conservation, carbon sequestration, and cultural heritage. Without accounting for these co-benefits, policy will continue to undervalue agroforestry's contribution to resilient food systems.

From a policy perspective, agroforestry is not currently embedded in policy frameworks. Venn and Burbi's (2023) recent study suggests that there is a need for a system to support the transfer of knowledge from research (and on-the-ground experience) into policy. They argued that the current lack of such systems creates a mutually reinforcing cycle in which positive interventions are not adequately supported by policy levers, hampering progress. Of the frameworks they evaluated, The FAO's 10 Principles for Agroecology demonstrated potential alignment of social and environmental objectives[134]. They argued in favour of adopting a food systems perspective to policy development, improved tools for knowledge exchange between practitioners, academia, and government, better integration between government bodies, and greater transparency in the practical methodologies behind proposed policy levers.

Without such a reorientation, agroforestry risks remaining a niche practice, despite its potential to serve as a cornerstone of a more resilient, equitable, and ecologically sound agricultural future.

Behaviour Change

An underrated yet increasingly well recognised lever for sustainable transitions comes in the form of peer-to-peer knowledge exchange within the farming community. In terms of uptake, studies have suggested that farmer-led knowledge exchange in the form of peer-to-peer networks is an effective tool for enabling the adoption of sustainable practices and of wider behaviour change[135,136,137], when compared to more 'top-down' approaches such as advisory services[138]. In the global south, the development of peer-to-peer networks stands as a grassroots challenge to the dominant trajectory of institutional support for sustainability interventions that support further intensification of food production[139].

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Within an academic context, the norm generally continues to be that farmers are not integrated into the co-design process beyond consultation, or the sharing of experiences. Many researchers do not have an agricultural background and the research cycle can take a number of years to complete, highlighting the importance of farmer collaboration in identifying relevant research questions, ensuring they are reflective of real and contemporary agricultural practices on the ground, and feeding into methodology and project design[140]. At a wider scale, there is a lack of 'soft' infrastructure for knowledge exchange[141]. There is also a need for regionally appropriate extension services to provide tailored advice on sustainability practices, particularly including those with lower-uptake such as low-input and circular practices[142].

The successful implementation of circular principles in multifunctional land use systems requires systems thinking approaches that recognize the complex interactions between social and ecological components. Research from Oxford examining the reasons for non-adoption of practices such as agroforestry, herbal leys, and rotational grazing found that farmers understood the potential benefits of these practices, but that their actual uptake remained limited[143]. This stemmed from what the authors describe as "rational non-adoption"; considered and deliberate decisions based on practical constraints, economic realities, and farm-level priorities.

One of the most prominent barriers identified was the high upfront cost associated with adopting these systems[144]. For example, agroforestry often required significant investment in fencing, planting, or infrastructure. For many farmers operating on tight margins, the financial risk associated with such investments was viewed as too great, particularly given the uncertain or long-term nature of the returns.

A second key barrier was a lack of alignment with existing farm objectives or systems. In many cases, the practices being promoted did not fit with the farm's current structure, business model, or long-term goals. This was particularly true for integrated crop-livestock systems, which were often perceived as overly complex or incompatible with simplified, efficient farming operations. The farmers interviewed in the report also expressed concerns about the uncertainty of benefits, especially in economic terms; although the environmental advantages were generally accepted, there was a reluctance to adopt practices without clear, reliable evidence that they would also deliver tangible economic gains[145]. Another important theme was the complexity of these practices compared to conventional approaches. The management requirements were perceived as higher, and the outcomes less predictable. Many farmers felt that their existing systems were already functioning well, and that adopting more complex methods introduced unnecessary risk and complication[146].

Ultimately, while environmental awareness among farmers may be strong, this alone is insufficient to drive widespread change. Without greater support to reduce financial risk, more robust evidence of economic returns, and better demonstration of how these systems can be integrated into existing operations, adoption of agroecological practices may remain limited.

These findings underscore the importance of policy design, knowledge exchange, and economic incentives in encouraging meaningful transitions toward more sustainable farming systems in the UK.

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Areas for further research

As described in Part 1 (*Multifunctional Metrics: Rethinking sustainability in food systems*), our current metrics and methods of evaluation are not well suited to more complex multifunctional systems like those examined in these case studies. We need more holistic methods of evaluation that can better assess the benefits and negative impacts of greater adoptions of these practices.

Pending such a transformational shift however, there are several key evidence gaps that should be addressed in order to better understand the potential for the above practices to contribute to the UK's path towards Net Zero, and sustainability more widely. These include:

- Modelling carbon storage potential of silvopasture and silvoarable practices across different proportions of UK agricultural areas, both as an alternative to and complementary with land-sparing approaches.
- Researching the potential effect of increased availability of tree fodder from agroforestry systems to reduce methane emissions in grazing livestock, and improve productivity.
- Improved understanding of ecosystem services and carbon storage under diverse permanent pastures, under different management regimes (particularly AMP grazing) using on-farm data.
- Modelling monogastric populations constrained by feeding from food waste, co- and by-products, particularly in scenarios where food waste is reduced[147].
- Quantifying the climate and productivity impacts of a reduction of inputs (e.g. nitrogen-based fertilisers or feeds) in both ruminant livestock and arable systems, and the trade-offs between greater use of livestock in arable systems (related to the above).
- Research into the impacts of AMP grazing specifically in integrated crop-livestock systems.
- Evaluation of establishment costs of the interventions in a UK context.

Regardless, long-term modelling is essential in order to improve the robustness of data to aid decision-making.

[147] The feeding of catering and household food waste products is currently prohibited by legislation, while the feeding of co- and by-products directly from food production (e.g. potatoes from the farm) or from manufacturing (such as brewers grains, liquid whey, and biscuit or bread meal) are permitted under strict conditions.

Where Do We Go From Here?

To support a transition to more sustainable, particularly low-input, agricultural practices in the UK, a coordinated and long-term approach is required across policy, research, and funding.

At the broadest level, the UK needs to reframe how land is valued and managed. Land must be managed not only for food production, but also for biodiversity, carbon storage, water regulation, and cultural value[148]. There is a similar need to move away from "single solution problem solving"[149], towards ones that recognise the relationships between different crises, and have the capacity to address them. This requires a policy environment that supports multifunctionality, encouraging land managers to deliver a broader set of public goods, rather than focusing solely on yield or economic return.

To achieve this, policy must move away from siloed, sector-specific approaches and instead support integrated land use. However, this integration requires supportive regulation, advisory services, and incentives that recognise the complexity and benefits of mixed systems.

In parallel, research must provide the evidence base to guide and justify these changes. There is a clear need for more UK-specific studies on the performance of low-input systems; how they affect yields, resilience, biodiversity, and profitability. Without robust data, it is difficult for policymakers to design effective schemes or for farmers to make informed decisions.

Moreover, research should not be confined to academic institutions. There is a real need for farmer-led innovation and knowledge exchange[150]. Demonstration farms, peer-to-peer learning, and co-produced research can help ensure that new practices are practical, scalable, and regionally appropriate. This is especially important for low-input systems, which often rely on local knowledge and adaptive management rather than standardised inputs.

Funding, finally, is the glue that holds this transition together. Farmers need financial support to cover the upfront costs of change. Public and private investment is needed not only on farms, but also in infrastructure, training, and market development[151].

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Credits

Charlotte Wheeler

Charlotte has worked in the agricultural sector for the past decade+, as a farmer and in academia. As Champion, she worked for Pasture for Life, as Research Officer, synthesising relevant research for a farming audience, as well as working on an inter-organisational project on the development of local and alternative supply chains. Charlotte is interested in exploring the role that agroecology can play in contributing to the UK food system's resilience to climate change, and the synergies between low-input farming, biodiversity restoration, and equitable, just food systems. She currently works as a consultant for Agriculture and Environment Policy Consultant at ICF.

AFN Network+

The AFN Network+ (UKRI Agri-food for Net Zero Network+) is a unique network of 3,100+ academics, researchers, third sector organisations, policy makers, and agri-food industry professionals from farmers to retailers. Together, we are working to identify key research gaps that may be holding the UK food system back from transitioning towards a net zero UK by 2050, while also enhancing biodiversity and healthy ecosystems, nurturing livelihoods, supporting healthy consumer habits, and minimising the environmental impacts of overseas trade. Our findings will inform the next decade of research investments in this area by UKRI (our funder and the UK research councils umbrella organisation).

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