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Organic farming, net zero targets and the impact of a changing climate – an evidence review

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1 Executive summary

1.1 Aims

The Scottish Government is committed to support the transition to net zero, whilst restoring and regenerating biodiversity. Organic farming practices have the potential to deliver to both agendas.

This Rapid Evidence Assessment (REA) and stakeholder engagement assesses the evidence for organic farming practices that contribute to the Biodiversity Strategy targets, a reduction in greenhouse gas emissions and making Scottish agricultural systems more resilient to the projected climatic conditions of 2045 (adaptation).

The review assessed greenhouse gas emissions in terms of both a reduction in emissions and an increase in soil carbon.

1.2 Key Findings

The stakeholders emphasised that organic farming is a holistic approach to farming the land, and benefits arise from the combination of management practices adopted. The literature review supported the holistic nature of organic farming.

We found that:

- Organic farming practices offer benefits to biodiversity, greenhouse gas emissions (GHGs), soil carbon, and how organic farming practices might help farmers adapt to a changing climate in Scotland over the next two decades to 2045 (termed adaptability) (Table 1).
- The inclusion of specific measures such as leys and cover crops, organic bulky materials and crop residue management in organic systems tends to increase the soil carbon.

  - In terms of reducing GHGs, these can be achieved through potential reductions of on-farm emissions, although these are variable, and reductions of purchased inputs and the transport associated with these inputs.
  - However, the cost of these benefits is a reduction in yield, potentially increasing global emissions due to the requirement for increased food production elsewhere (Smith et al. 2019).
- Organic systems are typically more diverse than conventional systems (Reumaux et al. 2023).
  - At the farm level, the wider range of crops creates a mosaic of habitats, while at the field level, intercropping, varietal mixes and a greater prevalence of weeds creates a variety of microhabitats.
  - Diversity at the farm, field and microhabitat level has positive implications for biodiversity.
  - Organic management practices tend to increase resilience making the farming systems more capable of dealing with the weather conditions projected for 2045.

Table 1. Summary of impacts of practices on biodiversity, soil carbon, GHGs and adaptation gathered from the Rapid Evidence Assessment (REA) and the Stakeholder workshops (S/H); green indicates a positive response (+), yellow neutral (n) and red negative (-). Blank cells indicate insufficient evidence.

Management Practices	**Biodiversity**		**Soil Carbon**		**GHGs**		**Adaptability**	
	REA	S/H	REA	S/H	REA	S/H	REA	S/H
Organic farming	+	+	+	+	+	+	+	+
Rotation management	+		+				n	
Reliance on legumes	+	+	+	+	+	+		
Increasing in field crop diversity	n						+	
Cover crops	n		+		n			
Crop residues	+		+		-		n	
Use of bulky organic materials	n	n	+	+	n			+
No synthetic inputs – weed control	+	+		+	-		+	+
No synthetic inputs - pest control	+	+		+	+		+	+
No synthetic inputs - disease control	+	+		+	+		+	+
Tillage – reduced	n	n	+	n	n	+	n	
Grazing practices	+			n	+		-	
Veterinary products	+							
Animal health management					+			

1.3 Gaps

- There is lack of evidence on the trade-offs between the individual organic management practices and the ecosystem services delivered.
- Although there is evidence that organic management practices can increase soil carbon, there is a need for better quantification of the long-term potential.
- There is a lack of evidence of the cumulative benefits of organic management practices on GHGs coming from the multi-year application of crop and livestock rotations.
- Continual development of carbon calculators to better incorporate updated science and data is required to help support the farming community make informed decisions.
- There is a need to increase the focus on developing systems that have the resilience to cope with the projected climate change.

1.4 Conclusions

The wider adoption of organic farming practices will benefit the environment. This would require support for the industry to transition and maintain the system. Advice and training would be required.

2 Contents

3 Introduction

The Scottish Government programme for a fairer, green Scotland, 2021-2022 is committed to doubling the land area devoted to organic farming by 2026, and supporting the growth of organic food production in Scotland. The Scottish Government is also committed to reducing greenhouse gas emissions (GHGs) and supporting the transition to net zero.

Climate is changing and we are likely to experience more extreme weather events including droughts and flooding. Therefore, it is crucial that agriculture takes steps to adapt their management practices to be fit for purpose in the face of the changing climate. At the same time, the Agricultural Reform Route Map sets out Scotland's commitment to deliver biodiversity conditionality in the future agricultural payments framework with wider targets including creating Nature Networks across Scotland connecting people with the natural environment. To achieve these targets, and increase the resilience of Scotland's food production systems, there is a need to enhance both above and below-ground biodiversity from our farmland.

The adoption of management practices associated with organic farming by the wider farming sector, and expansion of the organic sector has potential to deliver to the net zero targets for Scotland, enable farming to adapt to climate change and contribute to the Biodiversity Strategy.

This Rapid Evidence Assessment (REA) delves deeper into the specific agroecological practices that underpin organic farming systems in Scotland to assess the evidence for the contribution a wider adoption of organic farming practices can make to achieving these targets. This work therefore complements previous work undertaken for Climate X Change that explored the potential for a range of agroecological based farming approaches (including organic farming) to tackle the biodiversity and climate emergency (Cole et al. 2021).

3.1 What is 'organic' farming?

Organic farming, as defined by the EU council regulation 834/2007 is "a holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. It emphasizes the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems".

In Great Britain, organic farming is certified by Defra using the "Retained Council Regulation (EC) 834/2007" which sets out rules for labelling agricultural products and foodstuffs as 'organic'. Through the Windsor Framework, the EU organic regulations continue to apply in Northern Ireland. These rules certify the process of organic production rather than the actual product. As such they tend to deal with elements of the farming system that can be easily measured and controlled rather than dealing with more complex issues such as energy use or biodiversity. All food which is sold with the organic label must originate from producers or processors who are certified as organic and regularly inspected by an approved body (Chapter 12: Organic farming - GOV.UK (www.gov.uk))

Some producers adopt the agroecological principles of organic production but without engaging with the certification process, meaning they cannot label their produce as organic. Organic farmers are agricultural practitioners that do not use synthetic pesticides or synthetic fertilisers, and instead rely on cultural methods for weed and pest control as well as plant nutrient supply. Some farmers adopt the principles of organic farming but are not certified. Typically, organic farmers have mixed systems incorporating both animal and crop enterprises, including the use of crops and livestock bred without using genetic modification technology, that are adapted to local conditions wherever possible. However, there has been an increase in stockless (i.e. systems which do not rely on manure or other inputs from farmed livestock) organic systems in recent years.

Organic farming systems utilise diverse crop rotations, with carefully selected sequences of crops (both species and varieties), to help control pests, weeds and diseases. Nitrogen fixing crops such as clovers or grain legumes form an integral part of the system to sustain the fertility of the soils in the long-term (Watson et al. 2017). Organic farmers aim to utilise home grown, or locally grown, livestock feed. They will apply careful timing to all their field and animal care procedures, and other management practices. The latter includes the use of cover crops, green manures, timeliness and timing of field operations linked to soil and weather conditions, and practices such as composting of animal manure to aid weed control (Stockdale et al. 2001). Although organic farmers typically plough their field to control weeds, they do aim to minimise soil disturbance. Thus, reduced tillage has been included as a farm management option to be assessed.

Organic farming typically increases diversity within the crop (e.g. through intercropping and increased weed abundances) and at the wider farm level (e.g. through supporting a greater diversity of crops within the rotation) (Hardman, et al. 2016; Reumaux et al. 2023). With loss of habitat diversity identified as a major driver of biodiversity decline (Benton et al. 2003) this highlights the potential for organic farming to deliver biodiversity goals. In addition, the practices associated with organic farming tend to have positive effects on many supporting and regulating ecosystems services including water and soil quality, water regulation, pollination and pest and disease management (Tamburini et al. 2020; Beillouin et al. 2021). The focus of organic farm management practices to maintain soil fertility and exclude synthetic inputs offers the potential to increase soil carbon and reduce GHGs on a land area basis. However, organic management practices typically lead to a reduction in yield which may lead to the emissions per unit of product being similar or slightly higher than conventional systems (Smith et al. 2015). In addition, due to the lower yield, global emissions may increase due to the requirement for increased food production elsewhere to offset the lower yield (Smith et al. 2019).

3.2 Report focus

Organic farming is an holistic system with the promotion of biological processes and ecosystems at its core. Many of the individual practices or components of organic farming systems are slowly being adopted by some conventional farmers (e.g. the use of herbal leys and clovers in grassland).

This report focuses on **individual organic farming practices.** The range of practices assessed is based on Cole et al. (2021) and excludes the synergistic effects resulting from the adoption of multiple practices seen within commercial organic farming systems.

The focus of the report is on assessing the benefits and disbenefits of individual organic management practices on biodiversity, soil carbon, GHG mitigation, and adaptation to climate change. Consequently, documents that do not specifically focus on organic farming practices and the means to encourage or support the adoption of these practices by conventional and regenerative farmers are outside the scope of this report. A glossary of terms is provided in Section 9.

4 The evidence for benefits and disbenefits of organic management practices

The organic management practices that were selected for review were identified by Cole et al. (2021) as being typically adopted by organic farmers (Table 1). These included rotations, reliance on legumes, species and variety mixes, cover crops, crop residue management, use of organic fertiliser, no synthetic inputs, cultivation practices, livestock grazing management and the restricted use of veterinary products. The contribution of these selected organic management practices to deliver the climate change and biodiversity targets was assessed through a Rapid Evidence Assessment (REA), and stakeholder workshops. The impact of organic management practices on climate change has been considered in terms of both mitigation and adaptation. The mitigation contribution has been described in terms of the effects on soil carbon storage and GHG, where GHGs include nitrous oxide and methane emissions from crop, soil and livestock management and carbon dioxide from energy use. Six of the management practices were presented in the stakeholder workshops, although the stakeholders comments covered a broader range. Details of the methodology are set out in Annex 1.

An overview of the effects of organic management practices on biodiversity, soil carbon, GHGs and how organic farming practices might help farmers adapt to a changing climate in Scotland over the next two decades to 2045 (termed adaptability) as found in this project are shown in Table 1. The evidence assessed indicates that organic management practices tend to be beneficial for biodiversity and soil carbon. With respect to GHGs, Eory et al. (2023) identified that cover crops, and legume grass mixtures, practices associated with organic farming, reduced emissions, although this is expressed on a per area basis. Nevertheless, crop residue management may be a hot spot for nitrous oxide emissions while mechanical weeding increases fuel use. Organic management practices also tend to make the system more resilient, and hence better able to adapt to the projected weather conditions of 2045.

Table 1. Summary of impacts of practices on biodiversity, soil carbon, GHGs and adaptation gathered from the Rapid Evidence Assessment (REA) and the Stakeholder workshops (SHolder); green (+) indicates a positive response, yellow (n) neutral and red (-) negative. Blank cells indicate insufficient evidence.

Management Practices	**Biodiversity**		**Soil Carbon**		**GHGs**		**Adaptability**	
	REA	S/H	REA	S/H	REA	S/H	REA	S/H
Organic farming	+	+	+	+	+	+	+	+
Rotation management	+		+				n	
Reliance on legumes	+	+	+	+	+	+		
Increasing in field crop diversity	n						+	
Cover crops	n		+		n			
Crop residues	+		+		-		n	
Use of bulky organic materials	n	n	+	+	n			+
No synthetic inputs – weed control	+	+		+	-		+	+
No synthetic inputs - pest control	+	+		+	+		+	+
No synthetic inputs - disease control	+	+		+	+		+	+
Tillage – reduced	n	n	+	n	n	+	n	
Grazing practices	+			n	+		-	
Veterinary products	+							
Animal health management					+			

4.1 Organic Farming – holistic assessment

Organic farming is a systems approach to farming the land, and hence the environmental goods and services delivered are not easily attributable to individual practices. Consequently, rather than investigating specific practices in organic farming, most of the literature takes a systems approach when exploring differences between conventional and organic farming systems. This section summarises the key impacts on the holistic assessment of organic farming.

The literature therefore focusses on comparing a combination of management actions that characterise organic systems, typically investigating the consequences of:

- the exclusion of agrochemical inputs (e.g. inorganic fertilisers, herbicides, fungicides, and insecticides)
- reliance on organic manures
- the inclusion of pasture and legumes within the rotation

Furthermore, organic farms also tend to have higher habitat diversity (Hardman, et al. 2016). In a limited range of studies, lower water run-off and greater water infiltration was observed in organically managed treatments (encompassing a range of factors indicated above) compared to conventionally managed ones. A combination of management strategies is also used on organic livestock farms (e.g. lower concentrate feeding, more robust breeds, more use of pasture etc.) which also makes identification of the key causative factors difficult. Moreover, many of these practices are not exclusive to organic farm management and several are increasingly utilised in systems that are not certified as organic, and therefore arguably labelled conventional. This makes it difficult to determine the key factors exclusive to organic management that drive impacts.

Biodiversity

When comparing organic and conventional farming systems, impacts of organic farming on biodiversity were typically positive or neutral, with negative impacts rarely observed. Impacts differed depending on context (e.g. arable versus grassland, landscape type) and group of organisms (taxa).

Typically, plants benefitted from organic farming practices (Rotchés-Ribalta et al. 2020; Dobben, et al. 2019; Happe et al. 2018; Albrecht et al. 2020), and this was more pronounced in arable situations (Gabriel et al. 2010; Gibson et al. 2007; Schumacher et al. 2018) and for insect pollinated plants (Happe et al. 2018; Geppert et al. 2020; Gabriel and Tscharntke 2007).

Impacts on plant communities, were strongest within fields, but effects were often found to spill over to adjacent field margins and hedgerows (Happe et al. 2018; Gabriel and Tscharntke 2007; Boinot et al. 2022; Rundlöf et al. 2010; Gabriel et al. 2010). The greater abundance and diversity of crops and weeds in organic systems often result in a greater abundance and diversity of both pest insects, e.g. aphids, as well as their enemies; aphid-parasitoids and predators such as ladybirds (Puech et al. 2014; Sidauruk and Sipayung 2018; Birkhofer et al. 2016; Caballero-López et al. 2012).

The higher abundance and richness of flowers both in the crop and in the field margins typically attracted more pollinating insects including butterflies (Hardman et al. 2016; Feber et al. 2007; Gabriel et al. 2010), solitary bees (Happe et al. 2018), hoverflies (Geppert et al. 2020; Power, et al. 2016) and bumblebees (Sidemo-Holm et al. 2021, Geppert al. 2020) with threatened bumblebees particularly benefitting (Marja et al. 2018). Impacts on pollinators were, however, context specific with some studies detecting no impacts on bumblebees (Happe et al. 2018; Hardman et al. 2016) and solitary bees (Gabriel et al. 2010; Hardman et al. 2016). Only one study found negative effects of organic farming on pollinators, specifically hoverfly adults. This trend was not found for larvae and was attributed to spill over, where organic farms acted as a source of adults that spilled over to neighbouring conventional farms (Gabriel et al. 2010).

Assessments of the impact of organic farming on organisms that feed on dead and decaying material (for example, earthworms) showed inconclusive results. Studies on earthworms found both positive (Pelosi et al. 2015) and neutral effects (Pelosi et al. 2009). For organisms that kill other organisms, and which could be considered natural predators for the control of pests (natural enemies), impacts varied across functional groups with characteristics such as food preferences, ability to move location and how they hunt prey coming into play (Boeraeve et al. 2022; Chemlik et al. 2019; Gallé et al. 2019). For example, ground hunting spiders which typically have low dispersal capabilities were favoured in organic systems (Boeraeve et al. 2022; Feber et al. 2015) while impacts on more mobile web building species were neutral (Boeraeve et al. 2022; Feber et al.

2015). Organic farms, particularly if conservation tillage is adopted and/or grass leys are included in the rotation, are likely to provide greater opportunities for less mobile spiders to overwinter in field. Mobile species, such as money spiders, are less impacted by infield disturbances as they quickly disperse from surrounding habitats by ballooning. Due to their presence in fields early in the season, ground beetles were found to be sensitive to spring cultivation which is more frequent in organic systems (Chemlik et al. 2019).

Studies exploring the impacts of organic farming on bird communities typically report positive (Marja et al. 2014) or neutral (Hardman et al. 2016) impacts. Most species had similar abundances in organic and conventional systems (Moorcroft et al. 2002; Henderson, et al. 2012). Positive impacts of organic farming were found for lapwing and woodpigeon with both species showing a strong association with pulses, common in organic rotation. Lapwings were also associated with grasslands and spring cereals, while woodpigeons were favoured by the higher area of uncropped land (Henderson, et al. 2012). Skylarks were also favoured by the presence of uncropped land, potentially due to a greater availability of insects during the breeding season (Henderson, et al. 2012). Only one study found negative impacts of organic farming on birds (Moorcroft et al. 2002). Skylarks were found to prefer conventional barley stubble over undersown organic wheat and the more open structure of barley increased seed accessibility and supported a higher abundance of broad-leaved weeds increasing the diversity of forage (Moorcroft et al. 2002). The experimental design, however, made it difficult to tease apart impacts of crop type, undersowing and organic farming.

Organic systems typically increase the diversity of weeds (Madsen et al. 2020). However, the abundance of weeds is influenced by the choice of crop, cover crop, cropping sequence and the application of farm-yard manure (Kuht et al. 2016; Madsen et al. 2016; Madsen et al. 2020).

Soil carbon

Long-term studies indicate that the soil carbon in organic systems is higher than in conventional systems (Leifield and Fuhrer 2010; Gattinger et al. 2012; Colombi et al. 2019). There is conflicting evidence as to the cause of the increase in soil carbon in organic systems. In the meta-analyses by Leifield and Fuhrer (2010) and Gattinger et al. (2012), the increase in soil carbon was attributed to the increased level carbon in the organic material added to organic systems. The composition of the rotation is also influential, although the incorporation of forage legumes in the rotation was not a contributing factor (Gattinger et al. 2012). However, a recent study showed that the differences were not due to the quantity of carbon returned as manures or crop residues but were influenced by improved soil structure (Colombi et al. 2019). Nevertheless, the organic conventionally ploughed soils had higher soil carbon contents than either the conventionally ploughed or reduced till farmland. In organic systems, the inclusion of green manures, farm-yard manure, residue management and the inclusion of cover crops in the rotation all potentially contribute to the enhancement of soil carbon stocks (Gattinger et al. 2012; Hu et al. 2020). Their inclusion is crucial for maintaining the fertility of organic systems (Córdoba et al. 2018).

Greenhouse gas emissions

Agriculture has a significant impact on climate change through the emission of GHGs in the form of nitrous oxide, methane and carbon dioxide. Nitrous oxide results from the use of organic and synthetic fertilisers, crop residue management, and manure management. Methane emissions are also affected by manure management and by livestock production efficiency which is influenced by animal genetics, animal feeding practices and animal health and welfare status. The energy use on-farm is the primary cause of the emissions of carbon dioxide. Emissions arise from the transportation of inputs and outputs and those embedded in the production of inputs.

Nitrous oxide emissions were generally lower in organic treatments than conventional ones when based on output per unit land area (Autret et al. 2019; Biernat et al. 2020). However, the emissions on a yield-scaled basis tend to be similar or higher for organic systems (Pugesgaard et al. 2017; Skinner et al. 2019). Methane emissions from livestock were increased by converting to an organic system, but these were offset by the reduction in emissions from feed production (Gross et al. 2022).

The impact of the energy use on GHGs from organic systems compared to conventional systems was a function of the enterprise type (Smith et al. 2015). Arable crops were either negative or neutral, and livestock enterprises had positive, neutral, and negative responses. At the farm level, the energy use for mechanical weeding is higher for organic systems though this is offset by the reduction in energy use associated with the application and production of agrochemicals (Mäder et al. 2002; Aggestam and Buick 2017). The off-farm energy use was also a function of the enterprise type (Smith et al. 2015). Thus, the GHGs per unit of product for organic systems may be lower or higher than observed in conventional system depending on both the specific management practices and the type of product produced (e.g. Haas et al. 2001; Bos et al. 2007). However, because organic systems are lower yielding, the total global emissions may increase due to increased food production elsewhere (Smith et al. 2019).

Adaptability

The soil organic carbon and the water holding capacity of soils that were managed organically but were conventionally ploughed tended to be greater than conventionally managed soils that were either ploughed or were not tilled (Colombi et al. 2019).

Stakeholder views

The view that organic farming is a holistic approach was supported by the stakeholders. There were strong views that organic farming is an holistic approach and should not be decomposed into individual practices, as this conflicts with the ethos of organic farming. Unlike regenerative agriculture, organic farming is defined by specified standards.

The stakeholders reported that the current carbon calculators do not take account of the holistic approach, and in particular the role of legume-based grasslands on soil carbon. Stakeholders considered that organic farms are less intensive than conventional farms which makes them more resilient to environmental shocks, e.g. weather extremes.

4.2 Specific management practices

This section will examine the evidence for benefits and disbenefits of individual farm management practices on biodiversity, soil carbon, GHGs and adaptability. Where the stakeholders have expressed views on the specific management practices, these have also been included in each sub-section.

4.2.1. Rotation management

A crop rotation is the sequence of different crops that are grown over a number of years. Typically, in organic systems, the rotation is more diverse than conventional farming and contains plants from different families, e.g. cereals, oilseeds, legumes. The organic rotation design is fundamental to maintaining soil fertility, and controlling pests, diseases and weeds (Watson et al. 2006). The rotation will typically include legumes to build soil nitrogen, and the application of livestock manures and crop residues will be carefully managed to recycle nutrients within the system.

Biodiversity

The simplification of landscape structure (e.g. loss of hedges and walls, and simplification of crop rotations) is a key driver of declines in farmland biodiversity (Benton et al. 2003). Crop rotations support a patchwork of different infield landcovers (e.g. oilseed rape, field beans), and creates temporal diversity (e.g. spring sown and winter sown crops), thus enhancing landscape diversity. Diverse landscapes, with a range of different habitats provide a variety of different resources (diverse food resources, nesting habitat, overwintering sites) which not only support different species, but also help ensure that individuals can meet their resource requirements through their lifespan. New evidence has found that crop rotation diversity is higher in organic farming particularly in more productive land (Reumaux et al. 2023). The wider research indicates that more diverse crop rotations are likely to have positive impacts on biodiversity, however, research in this area is lacking (Dicks et al. 2020).

Soil carbon

There is evidence from an international meta-analysis that suggests that diverse rotations result in a small but significant increase in the soil carbon relative to a cereal monoculture (McDaniel et al. 2014, cited in Smith et al. 2018). The inclusions of leys in an arable rotation also increases the soil carbon stocks (Jordon et al. 2022).

Greenhouse gas emissions

From the REA, no relevant papers were found.

Adaptability

Organic crop rotations are frequently more diverse which builds resilience into the system by reducing the overall impact of crop failures due to abiotic and biotic factors. Such crop losses can have dire consequences for systems reliant on the yields of a few crop species. Organic systems also provide more niches for weeds than conventional rotations which reduces the chance of single weed species dominating (Ulber et al. 2009; Benaragama et al. 2019; Seipel et al. 2022). The combination of less diverse rotations and herbicides results in conventional rotations having lower weed species diversity and richness when compared to organic crop rotations (Ulber et al. 2009; Schumacher et al. 2018). Including species (e.g. plantain or chicory) with tap roots in the rotation can help to alleviate compaction and improve the drainage (Lynch and Wojciechowski 2015 cited in Smith et al. 2018).

4.2.2. Reliance on legumes

Organic systems are heavily reliant on legumes within the crop rotation or incorporated into grass leys. This is because legumes can fix nitrogen from the atmosphere, and hence they build fertility and provide nitrogen to the other crops in the rotation. Legumes typically used in Scottish organic systems include clovers, vetches, peas and beans.

Most of the organic land in Scotland is grassland. White clover is the most common legume incorporated into grassland seed mixtures alongside grasses and herbs and is used for both grazing and silage. For silage production red clover/ryegrass leys are also used. Grass/legume leys are typically established by undersowing the seed into a preceding arable crop (e.g. oats).

In stockless organic systems, legume based green manures (a crop which is grown to incorporate into the soil) are typically included in the rotation, while in stocked systems, grass-legume leys (generally multi-species including one or more clovers but sometimes other forage legumes too) are part of the rotation, which are grazed by ruminant livestock.

Biodiversity

The use of legumes in both grassland and arable systems will enhance heterogeneity at the micro-habitat and farm scale which is likely to have positive implications for biodiversity (Benton et al. 2003). Legumes provide profitable sources of nectar and pollen, and the loss of legume-rich habitats is linked to pollinator declines (Goulson et al. 2008; Kleijn and Raemakers 2008). The wider research exploring the inclusion of grass clover leys in arable systems has found lower levels of pest and positive benefits to spider but not ground beetles (Dicks et al. 2020).

Soil carbon

Increasing the proportion of legumes in the rotation has a positive impact on soil carbon, with perennial legumes having a larger effect than annual legumes (Feiziene et al. 2015).

Greenhouse gas emissions

The nitrous oxide released by legumes is lower than crops receiving synthetic fertiliser (Stagnari et al. 2017 as cited by Smith et al. 2018). There is also a reduction in GHGs associated with the transport and the production of synthetic fertiliser.

Adaptability

From the REA, no relevant papers were found.

Stakeholder views

The benefits of legumes for both above and belowground biodiversity was supported by the stakeholders. The inclusion of legumes in organic systems reduces GHGs due to the reduction in the requirement for synthetic fertilisers, providing soil cover, and by reducing the need for bought in feed for livestock. The stakeholders also identified that forage legumes enhance the soil organic matter content, which will improve the ability of the soil to retain water in drought conditions. Grain legumes, and in particular peas can be difficult to grow in Scottish conditions. There is a need to develop cultivars and mixtures that are appropriate to Scottish conditions, this is particularly important for grain legumes. This constraint is coupled with a limited market for the product.

4.2.3. Increasing in-field crop diversity (e.g. intercropping, varietal mixes)

Field crop diversity means that more than one variety or species are grown together in the same field. In some cases, they may be mixed together, in other cases they may be sown separately in strips. In organic systems, undersowing an arable crop with clover or grass-clover is a standard practice. A form of field crop diversity is intercropping (e.g. growing a legume and a cereal together which may be harvested as a whole crop for feed or harvested and separated for the grain). Varietal mixes, where multiple varieties of the same species (e.g. barley) are sown in combination in a field is also a form of increasing field crop diversity. However, there may issues about the acceptability of mixtures by the food and drink industries.

Biodiversity

Increasing crop genetic diversity through intercropping or varietal mixes is likely to increase the diversity of food resources for above and below ground biota. Intercropping is also likely to enhance the structural diversity of a field, resulting in a broader array of microhabitats with positive implications to biodiversity. A study exploring varietal mixes found no impacts on wild plant diversity but did find positive impacts on above (spiders and carabids) and below ground (Collembola) arthropods (Chateil et al. 2013). These findings support wider research which illustrates positive impacts of intercropping and under-sowing cereals across a range of organisms (taxa) (Dicks et al. 2020). There is, however, evidence that while undersown and conventional stubble fields have similar seed densities, that the more open structure of conventional stubble increases the accessibility of seeds for granivorous birds (Moorcroft et al. 2002). The experimental design, however, made it difficult to tease apart impacts of crop type, undersowing and organic practices indicating a potential area for future research.

Soil carbon

From the REA, there was no evidence of increasing in-field crop diversity impacting on soil carbon. Wider research has found a reduction in soil carbon in intercropped systems, and this was attributed to a higher diversity of below ground activity stimulating soil processes such as the decomposition of organic matter (Brooker et al. 2023).

Greenhouse gas emissions

From the REA, no relevant papers were found. Nevertheless, in varietal mixes, the risk of disease is reduced and therefore the need for the application of synthetic pesticides is reduced. In addition, for legume-based intercrops, the requirement for synthetic fertiliser is reduced. The reduction in application of synthetic inputs will reduce GHG emissions.

Adaptability

Productivity and stability of the yield between years often increases with diversity, due to the increased resilience of the system (Johnson et al. 1996) which is vital in adapting to future climate conditions. Broader research has highlighted that in Scotland that the benefits of intercropping compared to sole crops might increase if summers become warmer and drier as predicted by climate models (Brooker et al. 2023). Genetically diverse plant material (e.g. composite cross populations or varietal mixtures) often perform best under organic systems whereas genetically uniform material (e.g. varieties) often do best under conventional farm management systems for which they have been bred (Legzdiņa et al. 2022). Conventional crop varieties are genetic monocultures bred for high input conventional systems in which synthetic inputs (fertiliser and pesticides) are used to maintain the growing environment. Without access to such inputs organic cropping materials must be diverse in character to suit the more diverse growing environment (Legzdiņa et al. 2022). Trials for new varieties are typically conducted in conventional systems with high levels of synthetic inputs. As a result, varietal selection focuses solely on yield optimisation and disease resistance. Additional focus to determine varieties that perform well in low input systems would help advance efficiency in organic, and other low input, systems.

Stakeholder views

Companion cropping are alternatives to the application of synthetic pesticides as these reduce the risk of a reduction in yield due to plant diseases. This is because of the genetic variation associated with the different species and varieties sown.

4.2.4. Cover crops

Cover crops are grown seasonally between the main arable crops and are not normally used to produce a product for sale. The inclusion of cover crops in the rotation avoids bare soil being exposed, and reduces the risk of soil erosion, and nutrient losses. In organic systems the cover crop may be grazed off by livestock before the residues (roots and stubble) are incorporated into soil as the ground is prepared for the next crop. This practice also occurs on conventional farms growing spring crops, although it is more commonly found on organic systems. In conventional systems, cover crops are often destroyed with herbicide prior to sowing of the following crop.

Biodiversity

Research exploring the impact of cover crops on biodiversity in organic systems was lacking, although the wider literature indicates positive impacts on earthworms (Pelosi 2009). Cover crops will reduce soil erosion, and therefore, they are likely to improve the ecological status of waterbodies. The impact of cover crops is likely to be dependent on both the method of destruction (e.g. cultivation versus grazing it bare and overseeding, or application of glyphosate to kill off the cover by conventional farmers) and the alternative land use. For example, winter stubble benefits a wide range of groups of organisms (taxa) (Dicks et al. 2020), and its destruction to establish cover crops could adversely impact on some species (e.g. seed eating birds). Comparing potential trade-offs across taxa provides an interesting area for future research. Cover crops tend to reduce weed growth (Madsen et al. 2016), although the weeds and weedbank are affected by the species included in the cover crop mixtures (Madsen et al. 2017).

Soil carbon

The result from a European meta-analysis of long-term studies indicates that the inclusion of cover crops do not lead to an increase in the soil carbon stocks (Jordon et al. 2021). The results of three long-term experiments in Denmark support this observation (Hu et al. 2018). In contrast, the results from a long-term organic trial in Estonia showed variability in the response of the soil carbon to the inclusion of cover crops in the rotation (Eremeev et al. 2020; Are et al. 2021; Kauer et al. 2021). This was influenced by the phase(s) in the rotation assessed.

Greenhouse gas emissions

There is limited evidence that indicates that the inclusion of a cover crop does not affect the nitrous oxide emission, although the choice of cover crop can influence the emissions, and the subsequent nitrogen benefit to the following crop (Li et al. 2015). Although the total emissions were not affected, the distribution of the emissions during the season were affected by whether the crop was harvested in the autumn or ploughed in just before sowing the following crop (Li et al. 2015).

Adaptability

Bare ground is more exposed to abiotic stresses such as wind erosion and rain compaction. Climatic changes may result in greater, and less predictable, changes and levels of abiotic stresses related to temperature, solar radiation and rainfall patterns. Cover crops offer protection from these stressors, but they also offer refuge for pathogens (e.g. clubroot), pests (e.g. slugs), and natural enemies (e.g. predatory beetles (Sereda et al. 2015). The challenge is achieving the right balance of crop species included in the cover crop and the timing of the operation to minimise pest damage. The choice of species included in the cover crop mix will also influence both the weed abundance and the diversity of weeds (Madsen et al. 2017). The inclusion of cover crops in the rotation may also reduce the water holding capacity of the soil (Are et al. 2021), putting the main crop at greater risk of drought. However, this is mitigated by the inclusion of bulky organic materials in the rotation (Are et al. 2021).

4.2.5. Crop residues

In organic farming, the crop residues (stubble) are typically left on the field after the crop has been harvested. The residues include straw that is chopped and returned but excludes straw which is harvested and used for bedding. Crop residues reduce the risk of erosion and are typically incorporated into the soil before planting the following crop. Their return supports the fertility of the organic system. In stockless organic systems, green manures (which contain legumes to build fertility) are typically included in the rotation. During the growing season, they will be cut several times with the residue left on the field. They will be incorporated before planting the following crop.

Biodiversity

The wider literature indicates that winter stubble provides a variety of resources for a range of organisms (taxa) including plants, insects, spiders, mammals and farmland birds (Dicks et al. 2020). Perhaps most notable is the potential for stubble to provide winter forage for seed eating birds such as yellowhammer and skylarks. Undersowing, a practice common in organic systems, however, can reduce the accessibility and diversity of seeds (Moorcroft et al. 2002). Although research exploring the impact of incorporating crop residues is limited, benefits on natural predators (natural enemies), specifically spiders and carabids, have been found (Sereda et al. 2015). It is likely that through benefitting soil health, the retention of residues will also benefit soil biodiversity.

Soil carbon

The inclusion of a cut and mulched green manure tends to increase the soil carbon stocks (Hu et al. 2018). Global meta-analysis indicate that the addition of crop residues enhances soil carbon stocks (Poeplau & Don 2014; Mcclelland et al. 2020). Nevertheless, the stability of the carbon will be dependent on the management practices adopted.

Greenhouse gas emissions

Crop residue nitrogen content is a major driver of nitrous oxide emissions (Pugesgaard et al. 2017).

Adaptability

Similarly to cover crops, crop residues offer protection from erosion and soil compaction. Crop residues such as straw/litter from previous crops help protect the soil from such stresses. They also offer refuge for pests, such as slugs, and predators, such as beetles (Sereda et al. 2015).

4.2.6. Use of bulky organic materials

Bulky organic materials include farmyard manure, compost, digestate and green waste. Farmyard manure might be produced on stocked farms and redistributed within the farm to crops or grassland destined for silage. Those without their own stock might import manures, or other bulky materials such as digestate or green waste compost (e.g. the manure from organic poultry units must be returned to organic land). As well as providing nitrogen, phosphorus and potassium, bulky manures also provide micronutrients to the crop. The nutrient content of the bulky organic material is a function of manure type (including livestock species), and the treatment of the bulky organic material. Again, these practices are not exclusive to organic farms. However, these approaches to nutrient and soil organic (carbon) management are predominant on organic farms where many conventional systems will combine bulky organic manures and synthetic fertilisers. Sewage sludge application is not permitted in organic production.

Biodiversity

The use of bulky organic materials is thought to enhance soil invertebrates that feed on dead and decaying material which in turn increases food supply for predatory arthropods in organic systems (Pfiffner and Luka 2003). The impact also varied with group of organisms (taxa), with wolf spiders and carabids typically having higher densities in organically fertilised plots, while money spiders and rove beetles had higher densities in plots receiving inorganic fertilisers, impacts however varied with crop type and year (Eyre et al. 2009). Exploration of the wider literature comparing inorganic fertilisers with organic materials, found organic fertilisers typically benefitted a range of organisms (taxa) including plants, collembola, earthworms, and predatory beetles (Dicks et al. 2020). Impacts, however, varied between taxa and effects were not always consistent with impacts on ground beetles, ranging from positive (Hance and Gregoirewibo 1987) to neutral (Birkhofer, et al. 2008). Animal dung can be contaminated with veterinary medicines and residues of wormers (i.e. ivermectin) can retain toxic effects to terrestrial and freshwater invertebrates (Sands and Noll 2022). Research comparing nutrient run-off from organic and inorganic fertilisers is inconclusive with some studies finding no impact, while another found greater runoff in plots receiving organic fertilisers (Dicks et al. 2020).

Soil carbon

The modelled estimates of the inclusion of bulky organic material in the rotations suggests that soil carbon will increase (Knudsen et al. 2014). The application of farmyard manure almost always improved soil carbon (e.g. Fließbach et al. 2007; Heinze et al. 2010; Are et al. 2021; Kauer et al. 2021; Alvarez 2022; Krause et al. 2022; Sosulski et al. 2023). The change in the soil carbon pools is influenced by the type of organic bulky material applied (Boldrini et al. 2007). For example, composting the manure before application is likely to have a greater impact on the soil carbon than uncomposted manure (Fließbach and Mäder 2000, cited in Smith et al. 2018). In addition, the crop may also influence the impact (e.g. there was no difference in the soil carbon for potatoes receiving either farm-yard manure or fertilisers (Eremeev et al. 2020)).

Greenhouse gas emissions

Replacing fertiliser inputs with organic manures had no significant effect on the on-farm emissions of nitrous oxide and methane in conventional systems (Skinner et al. 2019). Nevertheless, although the N inputs in the organic systems were approximately half of those applied in a similar conventional system, there was no impact on the yield-scaled emission (Skinner et al. 2019). As bulky manures have high concentrations of carbon and nitrogen there is an increased risk of nitrous oxide emissions when they are applied in wet conditions (Rodrigues 2006, cited in Smith et al. 2018).

Adaptability

From the REA, there was no evidence of bulky organic material on adaptability. However, treatment of manure can influence adaptability. The high temperatures achieved when manure is composted are known to kill plant disease and weed seeds (Litterick et al. 2003) and thus this practice is encouraged in organic farming.

Stakeholder views

The types of bulky organic manures and composted waste (e.g. sewage sludge) that can be used on organic farms are restricted. The addition of bulky manures has benefits for soil biodiversity, which provides feed for the birds. However, applying bulky manures which contain veterinary medicines can also have negative consequences for biodiversity, and their use has to be carefully managed to avoid pollution. Their application improves the soil structure, increases the soil organic matter, improves drainage and increases the water holding capacity of the soil. Consequently, the soil is more resilient to both drought and extreme rainfall events. With climate change, the risk of pests and diseases is likely to increase, and the use of bulky organic manures may reduce the risk. However, there is a huge knowledge gap in the interplay between crop nutrition and crop health.

4.2.7. No synthetic fertilisers, pesticides, herbicides

In organic systems the application of synthetic fertilisers, pesticides and herbicides is prohibited. Natural compounds can be used when there is a specific threat to the crop. Records which demonstrate the need for such an application must be kept.

Biodiversity

The use of inorganic fertilisers can result in nutrient leaching and run-off adversely impacting on freshwater biodiversity. A reduction in inorganic inputs can also benefit plant diversity (Koch and Meister 2000; Rotchés-Ribalta et al. 2020; Fonderflick et al. 2020; Dobben, et al. 2019) with positive implications to invertebrates. For example, unfertilised grasslands have been found to support more rare specialist moths (larvae associated with a limited number of plant species) (Mangels et al. 2017).

Reduction/or avoidance of herbicide applications results in richer, more abundant, plant assemblages (Fonderflick et al. 2020). Studies comparing plant communities in organic and conventional systems, typically identify that the lack of herbicides has a positive impact on biodiversity (Carrié et al. 2022; Sidemo-Holm et al. 2021) with effects most prevalent in arable fields. The positive impacts often extended to field margins due to lack of spray drift (Happe et al. 2018; Marja et al. 2018).

A reduction of pesticide use was found to have a positive impact on bats (Barré et al. 2018) and earthworm populations (Pélosi et al. 2013). Earthworms closest to the surface were particularly vulnerable to the application of synthetic products and impacts of insecticides were greater than either herbicides or fungicides (Pélosi et al. 2013). Impacts of plant protection products on ground beetles varied depending on diet and size (Eyre et al. 2012) and while the removal of insecticides did not impact on the density of natural predators of pests (e.g. ladybirds, lacewings and hoverflies), it increased the predator prey ratio suggesting that natural pest control is more effective in the absence of insecticides. Drawing from the wider literature, there is strong evidence that a reduction in synthetic fungicides, herbicides and insecticides benefits a range of groups of organisms (taxa) including invertebrates, plants and birds, although neutral and negative impacts are sometimes detected (Dicks et al. 2020).

Soil carbon

From the REA, no relevant papers were found.

Greenhouse gas emissions

The reduction in GHGs is due to the reduction in the number of tractor operations and the amount of agrochemicals and fertilisers applied as well as emissions associated with their manufacture. However, this reduction in emissions can be offset by an increased requirement for mechanical weeding and / or the application of bulk organic materials.

Adaptability

Resistant crop varieties and crop protection products currently form a significant component of crop protection programmes. However, crop breeding and the development of new pesticidal active ingredients takes many years. Although modelled projections of yield are expected to increase under climate change in high latitudes (Chaloner et al. 2021), the relative pressure from pests, weeds and disease could increase at such a rate that plant breeding and pesticidal development will not be able to keep pace (Chaloner et al. 2021; Steinberg and Gurr 2020). Biological approaches to crop protection confer adaptation to future pest and disease threats. Invertebrate pests are often more prevalent in organic systems (Krey et al. 2019) as is biological control through natural process such as predation and parasitism (Birkhofer et al. 2016; Caballero-López et al. 2012; Chabert and Sarthou 2020; Inclán et al. 2015; Sereda et al. 2015; Muneret et al. 2018; Sidauruk and Sipayung 2018). Reasons for this include a lack of synthetic insecticides which would kill beneficial insects and prey, and the greater food and habitat provision through the increased plant diversity in organic systems, which is achieved through more diverse rotations and the omission of herbicides. System (conventional, new and old organic fields) and landscape complexity (amount of pasture and the area of field borders, wild flower strips) affect pests, natural predators for the control of pests (natural enemies), and biological control services (Birkhofer et al. 2016; Török et al. 2021).

Stakeholder views

This is fundamental to organic farming as it supports biodiversity. The restrictions on synthetic products are defined. However, this is not the case for agroecological or regenerative systems. The restrictions imposed by the organic standards limit the ability of farmers to deal with weeds and pests, and therefore alternative methods are required. There was a view that additional research and sharing of good practice would help support farmers in dealing with these challenges. The lack of synthetic inputs helps to maintain healthy farm ecosystems which has benefits for the soil, and soil carbon storage as well as for above and belowground biodiversity. Healthy ecosystems also help buffer against unexpected fluctuations in weather and pest and disease pressures. However, although organic farmers cannot apply synthetic pesticides, they are able to apply a limited range of products in specific situations (e.g. copper oxychloride for blight control) that are damaging to nature. Application of these products are restricted in amount and only allowed where there is no successful alternative control mechanism (e.g. in the case of potato blight).

4.2.8. Tillage

Minimum till or zero till systems reduces the degree to which the soil is disturbed when the crop is sown. Stocked organic systems generally contain a ley phase established by undersowing the main crop with a grass-clover ley which reduces the amount of tillage compared with an all arable system. This ley is then left following harvest. Many arable crops can also be established by minimum till or zero till methods. Nevertheless, because of the need to control pests and weeds in organic systems through cultivation, minimum till or zero till systems are more often observed in non-organic systems.

Biodiversity

Research exploring the impact of reduced tillage (e.g. direct drill, and methods to reduce the depth of cultivations) on biodiversity in organic systems was inconclusive and dependant on the group of organisms (taxa) and context. Positive impacts were detected for bats (Barré et al. 2018). Effects on earthworms varied with crop type and tillage practice and ranged from negative to neutral (Metzke et al. 2007). The population of predators such as ladybirds and carabid beetles are often influenced by tillage frequency, whereas the population of parasitoids are rarely affected (Puech et al. 2014). Impacts of tillage on soil invertebrates may take years to develop, and short-term studies are unlikely to accurately reflect impacts. Nevertheless, there is evidence to suggest that nematodes are increased in reduced tillage systems (Schmidt et al. 2017, cited in Junge et al. 2020). The wider literature indicates that reduced tillage is likely to be beneficial with positive effects found for invertebrates, weeds and farmland birds. Effects however varied with taxa, crop type and tillage practice (Dicks et al. 2022).

In organic systems reduced tillage has been found to increase weed abundance (Armengot et al. 2015; Gronle et al. 2015; Benaragama et al. 2019; Seipel et al. 2022) with a particular increase in perennial weeds thus shifting the community composition of perennial and arable species, although not impacting species diversity itself (Armengot et al. 2015). Reduced/no till land often experiences more grass weed issues (typically low levels of dormancy) and sometimes less broad leaf weed problems as those seeds remain deep within the soil profile.

Soil carbon

Reduced tillage increases the soil carbon in the topsoil (Jordon et al. 2022; Szostek et al. 2022; Fotana et al. 2015). However, the effect is moderated by the soil texture (Fotana et al. 2015, Krauss et al. 2022), and the inclusion of green manures (Emmerling 2007) or composted manures (Krauss et al. 2017) in the rotation. Although the effect is reduced with soil depth (Jordon et al. 2022), the soil carbon in the total soil profile tends to increase (Krauss et al. 2022).

Greenhouse gas emissions

Tillage did not significantly affect either nitrous oxide or methane emissions (Krauss et al. 2017). The reduction in GHGs associated with organic production is due to the reduction in the number of tractor operations.

Adaptability

In reduced tillage systems, the organic matter in the topsoil increases, and hence increases the water holding capacity of the soil (Gronle et al. 2015). Drought, flooding and elevated temperatures have less effect on the soil microbial communities and plant health in reduced tillage systems (Kaurin et al. 2018).

Stakeholder views

Reduced tillage improves the soil structure and the soil biodiversity. However, the views of the viability of reduced tillage as a practice differed. They ranged from introducing tillage as a compulsory practice in organic systems to the requirement of organic farmers to use the plough at some points in the rotation to control the weeds. There were also concerns raised that promoting reduced tillage with conventional farmers would increase the use of glyphosate, which is used to kill the weeds, and therefore have negative consequences for biodiversity. It was also raised that there is evidence that pesticide and fertiliser use has increased in reduced tillage systems in the US. Some stakeholders held the view that the applicability of using reduced tillage methods was dependent on the soil type, weather conditions and the crop to be planted (e.g. it was also stated that spring barley is a difficult crop to establish using reduced tillage methods).

The benefits for GHGs are due to the reduced fuel use, and potentially a reduction in soil related GHGs which the stakeholders attributed to reduced leaching. It was also highlighted that the soil carbon sequestration may be short-term, and only affect the topsoil.

4.2.9. Grazing practices

The grazing practices adopted by the organic farmer are not just about maximising production. It is also imperative that the organic farmers consider the nutrient status of the soil, the botanical composition of the sward or forage and animal health and welfare is maintained. Organic certification in the UK requires that at least 60% of livestock diet is produced on farm, and there is a strong push towards pasture grazing. Consequently, organic systems often involve lower stocking densities, and/or more regenerative grazing management to optimise pasture use (e.g. rotational and mob grazing strategies). Mob grazing means that the field or part of the field is grazed very heavily for a short space of time (1-few days) till the grass height is approximately 10-20 cm. After grazing, the field is left for a considerable time to allow the field to recover (e.g. 60-80 days) meaning that the livestock are grazing tall, mature grass when they do return to the field (i.e. 30-60 cm). Short term leys are typically incorporated into organic systems, which improve soil fertility. Rotational grazing also involves moving animals from field to field, but typically the animals remain longer in each field (e.g. 3 – 7 days), and graze the grass sward down to a lower level (e.g. 5 cm). Rotational grazing involves a much shorter rest period (e.g. 15-30 days) and the grass is shorter when livestock re-enter (e.g. 8-10 cm). In addition to the traditional grazing of grasslands, farmers are also utilising cover crops, winter cereals and other forage crops to provide feed for ruminant livestock. Silvopastoralism (where trees and grazing systems are combined) is not commonly practised in Scotland.

Biodiversity

Grazing management influences the structure and composition of vegetation with both overgrazing and under-grazing having deleterious impacts on biodiversity (Pulungan et al. 2019). Site conditions (e.g. soil type, hydrology and topography) alongside management actions (i.e. timing, frequency, intensity and species of livestock) all have a role to play in determining impacts. When compared to continually grazed organic pastures, extensively mown meadows (i.e. two cuts annually), and to a lesser extent rotationally grazed pastures, supported higher densities of butterflies and more plant species indicative of species-rich grasslands (Kruse, et al. 2016). Mowing, however, is contrary to the push to prolong the grazing period to reduce the need for supplementary feeding and rotational grazing may provide a suitable compromise. The wider literature indicates positive impacts of agroecological grazing regimes (e.g. mob grazing, adaptive multi-paddock grazing) on micro and macro arthropod communities. Impacts on plants were found to vary with grasses tending to be favoured at the expense of shrubs and forbs (Morris 2021). Mob grazing regimes will enhance the structural diversity at the farm level such that flowers and seeds are more present at any one point in time, and this is likely to favour a range of species including seed eating birds and insect pollinators.

Soil carbon

The inclusion of short-term leys into the crop rotation increases the soil stocks with the impact increasing with the length of the ley (Jordon et al. 2022).

Greenhouse gas emissions

Animal growth can be promoted by providing access to good quality pasture (Pottier 2009; Keifer et al. 2014). There is some evidence that giving animals access to pasture when the grass is in a strong growth phase benefits animal growth (Novak and Fiorelli 2011). Grazing parasite-naïve animals on clean pasture reduces parasite loads, promoting animal health and therefore efficiency of growth (Cabaret et al. 2002). Factors that promote efficient growth will reduce GHGs/kg product.

Adaptability

Productivity and stability often increase with diversity, resulting in increased resilience of the system (Johnson et al. 1996). This is vital for adapting to future climate conditions. Weed communities from no-tillage and grazed/reduced-till organic systems are often distinct from the tilled organic community, underscoring the effect that tillage has on the assembly of weed communities (Seipel et al. 2022). Higher weed biomass is often observed in grazed/reduced-till organic systems (Seipel et al. 2022).

Stakeholder views

The ethos of organic ruminant livestock systems is the use of home-grown grazed and conserved forage with a minimum use of purchased concentrates. This reduces the GHGs associated with the transport and production of purchased concentrates.

Rotational or mob grazing of grasslands helps supports soil health and protects the soil from erosion, particularly during periods of heavy rain. This type of grazing contributes to plant diversity due to the rest periods. However, heavy stocking can have benefits as it allows the sward to open-up, permitting the dormant native species to re-emerge. This needs to be very carefully managed to be successful.

Innovative farmers are practicing these alternative grazing practices and believe there are benefits to soil carbon. Nevertheless, the conclusive evidence for the benefits was questioned by some stakeholders, and they identified that there is a need for scientific evidence of the benefits, disbenefits and unintended consequences of these practices.

Financial pressures on farms in 1980s led to specialisation and a reduction in the traditional mixed systems. There is increasing interest among specialist arable farmers to reintroduce some ruminant livestock back into their systems. For example, grazing of autumn sown arable crops (e.g. winter wheat). This reduces the risk of a yield loss that can result from frost damage over winter. There is also the potential to include herbal leys, which are more resilient to extreme weather and enhance above and belowground biodiversity. The introduction of grazing ruminant livestock into arable systems can improve the soil carbon due to the incorporation of a ley, the return of excreta and trampling of the ground. Nevertheless, there is a need to investigate the long-term consequences of reintegration of livestock on the environment.

4.2.10. Veterinary products

The use of veterinary products is restricted in organic farms. Organic farmers aim to treat their animals as little as possible without impacts on animal welfare. The impact of veterinary products on the environment is due to both the application of and the disposal of the product.

Biodiversity

Research into the use of veterinary products focusses on the adverse effects that wormer residues (e.g. avermectin) can have on dung communities (e.g. flies, dung beetles). Organic farms had higher abundances and richer communities of dung beetles and this was attributed to both a reduction in the use of avermectin and differences in landscape structure (Hutton and Giller 2003). Adverse impacts of wormer residues on invertebrates, are likely to have knock on effects for birds that feed on dung insects (e.g. starlings and choughs) (McCracken 1993).

Soil carbon

From the REA, no relevant papers were found.

Greenhouse gas emissions

From the REA, no relevant papers were found.

Adaptability

From the REA, no relevant papers were found.

Stakeholder views

This management practice reduces the antibiotics found in food.

4.2.11. Animal health

The principle of organic farming is that good care, housing and management of animals results in animals that are less susceptible to disease. Under IFOAM regulations, there are no limitations on the use of medicines (other than a longer withdrawal period for sale of milk/meat) so antibiotics can be used to treat disease and thus safeguard animal welfare. However, the use of alternative remedies is actively encouraged. Therefore, organic farming has the potential to reduce antimicrobial resistance in the human population (Mendes Costa et al. 2023). Housing and management practices such as the use of lower stocking densities and the use of feed-faces designed to allow all animals good access to feed, water and comfortable lying areas during housing periods is promoted. An extended period of grazing is also encouraged. While there is a great deal of variation between farms in the standards of animal welfare, studies have typically shown that these regulations will improve animal experience. Typically, also, the use of breeds and strains of animals that are somewhat less productive, but more 'robust' to environmental and other stressors is encouraged.

Biodiversity

From the REA, there was no evidence of better animal health impacting on biodiversity although the relationship has not been directly explored. However, yield reductions could result in offshoring biodiversity impacts.

Soil carbon

From the REA, there was no evidence of animal health impacting on soil carbon.

Greenhouse gas emissions

When animals are healthy, they are more likely to be more productive in terms of growth in beef or sheep and in milk yield for dairy cattle. While good animal health is equally possible on conventional farms, the lower intensity of management systems, such as the use of more 'robust' breeds, and the use of lower stocking densities and more dietary forage, means that animals in organic systems may be less susceptible to disease than animals on conventional farms (Bareille et al. 2022 commenting on studies on extensive ruminant systems in France). As episodes of disease or ill health reduce growth in beef and sheep animals, animals that have experienced disease will be at an older age when they reach slaughter weight than non-diseased counterparts. Given that the daily GHGs/animal/day is roughly the same irrespective of disease status, a higher age at slaughter means higher emissions per kg of output (Novak and Fiorelli 2011). Similarly, disease in dairy cattle is associated with reductions in milk yield, which equates to a higher emissions per kg of milk across the animal's lactation and lifetime.

Adaptability

From the REA, there was no evidence of animal health impacting on adaptability, but this relationship has not been formally addressed. A study considering extensive and intensive systems suggested that grazing animals may be more susceptible to parasitic infestations (Skuce et al. 2013).

Stakeholder views

The use of herd/flock health plans which incorporate herd / flock breeding objectives and management of the livestock has improved animal health, a principle which applies to organic farming as well as conventional systems. However, the restrictions on buying non-organic breeding stock and the ban on embryo transfer in organic farming has limited the opportunity to improve the genetic potential of the herds/flocks.

4.2.12. Additional relevant information raised by the stakeholders.

Buffer strips, field margins, hedges and trees were practices that were identified as having key benefits on organic farms for biodiversity, protecting watercourses, and providing wildlife corridors. Hedges and trees also provide shelter from extreme weather conditions for livestock.

There is a need for better engagement between science, practice and policy. The stakeholders also raised concerns about the feasibility of organic systems being part of the "less but better meat movement" due to the scalability and costs of production.

4.3 Gaps

The REA has illustrated that there is a body of work that assess the holistic nature of the benefits and disbenefits of organic farm management. However, the literature identified in the REA does not assess the trade-offs between the individual organic management practices and the ecosystem services delivered.

Although there is clear evidence that there are biodiversity benefits associated with organic farming, much of this has focussed on insect pollinators, predatory arthropods (particularly spiders and carabid beetles) and plants. Research on soil micro-arthropods, parasitoids, and mammals is comparatively scarce. This is most likely due to lack of expertise in taxonomy (e.g. parasitoids, springtails and soil mites) and difficulty in surveying (e.g. small mammals). Advancements in technology (e.g. soundscape analyses, metabarcoding and eDNA) may help to alleviate this bias.

Although there is evidence of organic management practices benefitting soil carbon, there is a need to have better quantification of the potential for these practices to sequester carbon. The influence of the practices needs to be studied on a long-term basis to ensure that the carbon added is not transient. There is also a lack of good studies that provide solid evidence of the impact of organic management practices on GHGs. It is also important that carbon calculators are further developed to fully account for the adoption of organic management practices.

In terms of the wider promotion of organic farming, there is a need to change the focus of plant breeding to produce varieties that will yield well under varied and less nutrient rich conditions, while also considering pest and disease resistance. There also needs to be more focus on breeding for novel and minor crops. This would help improve yields in organic farming and reduce losses due to weeds, pests and diseases. Improved yields would improve nutrient use efficiency and reduce nutrient losses as well as reduce GHGs per tonne of product.

Although there is evidence for the positive impact of organic management practices on the ability of Scottish agriculture to cope with projected climate change, the evidence is weak. Thus, there needs to be an increased focus on identifying the likely pressures on agriculture, and systems that have the resilience to cope with these stressors.

4.4 Limitations of the approach

Any REA or other type of review is limited by the date on which it is carried out. While in the review no evidence was found to indicate that crop diversity is higher in organic farming, a recent paper by Reumaux et al. (2023) indicates that crop rotation diversity is higher in organic farming particularly in more productive land. This is because conventional farming can utilise simpler crop sequences on good land due to the use of fertilisers and pesticides where organic production still requires diversity in the crop sequence to provide fertility via legumes and using crops with different susceptibilities to weeds, pests and diseases to manage crop health.

Undoubtedly the REA approach will not pick up all relevant literature because it uses title and keywords. If the authors do not use the term "organic farming" in the title and keywords, valuable literature can be missed. An example of this is the paper by Beillouin et al. (2021) entitled Positive but variable effects of crop diversification on biodiversity and ecosystem services.

A further limitation is that much evidence on, for example, the soil carbon benefits of grass/legumes leys has not been done in a specifically organic context although in reality the management of such leys is likely to be very similar whether organic or conventional.

5 PESTLE and SWOT Analysis

The PESTLE summary (Table 2) is informed by the current business and political environment. The SWOT (Table 3) summary is based on the literature review and the stakeholder engagement informed and has been informed by the PESTLE summary.

Table 2. PESTLE summary on the wider adoption of organic farm management practices

P	Clarity between a growth in certified organic systems and the adoption of selective organic farm management practices on a wider scale Support from government will be required to ensure economic stability of farmers adopting the practices. Complying with the climate change action plan, net zero Targets and the Biodiversity Action Plan Understanding of trade-offs related to implementation of different policies on biodiversity and climate change: • Food security • Affordable food
E	Farm viability Cost of support for transition to organic Cost of support for maintaining the farms as organic Cost of administering potential support and certification packages Cost of supporting knowledge exchange and skills development Cost to the farmer of changing their production systems both in terms of the costs of inputs and the value of the output.
S	Acceptance by the farming community of the benefits to their businesses of adopting all or some organic farm management practices Peer group acceptance of the adoption of the practices by a farmer. The development of social networks amongst farmers due to skill development and knowledge exchange requirement
T	The adoption of precision farm techniques to manage inputs, separate intercrop outputs The adoption of early warning animal disease technology National list trials for plant breeding for low input systems Organic Advisory support Training courses, modern apprenticeships, FE and HE level education
L	Legal framework for a support system which incorporates target metrics for support structures. Legal framework that specifies target metrics that have to be achieved for compliance.
E	Establish metrics that evaluate performance against biodiversity and net zero targets.

Table 3. SWOT summary on the wider adoption of organic farm management practices

Strengths	Weaknesses
Holistic systems that focus on agro-ecosystem health	Reduction in yield
Supports ecosystem resilience	Emissions intensity of production may increase
Benefits soil health	Constrained by regulation
Benefits biodiversity	Dependent on niche market which lacks infrastructure, e.g. abattoirs
Reducing industrial inputs and fossil fuel use– which reduces transport and the GHGs associated with production	The impact of the measures of GHG reduction may not be measured in C calculators
	The impact of the measures of GHG reduction may not be measured in the inventory process
	Lack of available training in organic agriculture and horticulture in Scotland
	Lack of knowledge on trade-offs between management practices
Opportunities	**Threats**
Wider adoption of organic management practices	Increased costs
Increase adoption of the practices will build biodiversity	Main streaming the niche a market which reduces the premium in the market place
Increase adoption of the practices will build soil health	Risk of reduced domestic production of key food products causing a food security issue
Increase adoption of the practices will builds the ability of the soil to cope with both drought and extreme rainfall events	Due to yield reductions, there is a risk of exporting emissions
Increased adoption of a range of practices could improve the matrix of landscape features	The pressure to reduce livestock numbers leads to a risk of insufficient livestock manure to maintain the system
Training and knowledge exchange will be required for successful uptake of the practice. This could include further development and role out of BASIS type qualifications	Accounting for the improvement in greenhouse gas emissions may not be tractable, and will be split between industrial, agriculture and LULUCF inventories
Co-operation between farmers may develop due to need for infrastructure and skills	The current c calculator methodologies cannot account for the effect some practices can have on emissions. This may be because there is insufficient quantitative information to parameterise the calculators.
Further development of Carbon Calculators to better describe the farm systems	Economic resilience is not supported
Regional demonstration hubs/farms for peer-to-peer learning	Risk of converting natural habitats to farmland to maintain production
Plant breeding focused on low input systems	Lack of skills and knowledge among the farming community to successfully incorporate the changed practices
	Investment in necessary capital and infrastructure by the farmers may be required to implement some of the practices
	Current plant breeding programmes are aimed at high input systems

6 Discussion

Organic farming is an holistic system, and this was emphasised through the stakeholder workshops. There was a strong view that it can be hard to disentangle the known and documented benefits of organic systems and attributes that impact on biodiversity and emissions to a specific management practice. This makes it challenging to adopt recommendations on specific practices at farm-scale. The holistic nature of organic systems was also evident from the REA.

Nevertheless, the REA and stakeholders identified that individual practices tend to be beneficial for the environment in their own right. The adoption of these practices will help to support the Biodiversity Strategy and contribute to net zero. There is concrete evidence to support the reduction in off-farm emissions. Due to the high variability in soil derived emissions, the evidence for a reduction in nitrous oxide emissions is less certain. Equally, at the systems level for ruminants, there are trade-offs in emissions due to an increased reliance on forage versus improved animal health.

Taking a more holistic approach, it is important to consider that while organic farming tends to positively impact on biodiversity, that yields are typically lower due to the restrictions in the use of synthetic agrochemicals. Based on European data, and assuming existing patterns of food production and food waste, it is estimated that the organic yield gap is 35%, which would require 50% more land to produce the same yields as obtained from a conventional system (Kirchmann 2019). The widespread conversion to organic farming is likely to result in the conversion of semi-natural habitats to agricultural land. An alternative approach could involve measures that can be implemented without significant impact on yield for example the diversification of productive habitats, reduction in field size, integration of semi-natural habitats within farmed landscapes and the use of precision agriculture techniques to improve efficiency of agrochemical use (Tscharntke et al. 2021).

The adoption of organic farming practices by the wider farming community will require support for the industry for the transition, and maintenance of the systems. In addition, advice and training will be required to ensure the successful implementation of the practices.

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8 Annex

8.1 Methodology

8.1.1. Rapid Evidence Assessment

A Rapid Evidence Assessment (REA) approach was adopted to assess the current state of the evidence of the benefits and disbenefits of organic farming practices on GHGs, biodiversity, and the potential of these practices to help farmers to adapt to the projected changes in weather that are likely to be experienced in 2045. While a REA is not as comprehensive as a systematic review, the REA is designed to be rigorous, transparent and minimise bias (Barends et al. 2017).

The search used to identify the literature was constrained to post 1999, and was:

(TITLE-ABS-KEY((organic* OR biodynamic* OR regenerativ* OR biologisch* OR oekologic*) W/0 (farm* OR field* OR agricultur* OR horticult*)) AND

TITLE-ABS-KEY(biodiversity OR "climate change" OR mitigat* OR adaptation OR "nitrous oxide" OR n2o OR "methane" OR ch4 OR sequestr* OR drought OR waterlog* OR flood* OR "heat stress" OR "cold stress" OR "greenhouse gas*" OR "soil carb" OR "soil organic carb*" OR soc OR "soil C" OR "soil organic c") AND

TITLE-ABS-KEY(rotation* OR variet* OR "species mix*" OR variet* OR "cultivar mix*" OR "fixing ley" OR tillage OR "soil cultiv*" OR "cover crop*" OR "living mulch" OR intercrop* OR undersow* OR "companion crop" OR "break crop*" OR manure* OR compost* OR biofert* OR irrigation OR pollinat* OR "crop resid*" OR "soil health" OR "soil fertilit*" OR "conservation area*" OR biostimulant OR "bio stimulant" OR "pre crop" OR precrop OR "soil amend*" OR IPM OR ICW OR IWM OR IDM OR "integrated pest" OR "integrated crop" OR "integrated weed" OR "integrated disease" OR fungicid* OR pesticid* OR herbicid* OR insecticid* OR molluscicid* OR nematicid* OR biofungicid* OR biopesticid* OR bioherbicid* OR bioinsecticid* OR biocontrol OR bioprotect* OR biofumig* OR "natural enem*" OR "plant protection product*" OR ppp OR graz* OR cattle OR sheep OR "veterinary treatment" OR "additives aid" OR "bioactive forage" OR "animal health") AND NOT

TITLE-ABS-KEY(chin* OR asia* OR africa OR brazil OR "south america" OR india* OR mediterran* OR subtropi* OR tropi* OR Thailand OR agroforestry OR "ecological status" OR model* OR lab* OR "sewage sludge*" OR biochar OR fish* OR aqua* OR viticul* OR rice OR vine* OR olive*)) AND

(EXCLUDE (PUBYEAR,1975) OR EXCLUDE (PUBYEAR,1987) OR EXCLUDE (PUBYEAR,1990) OR EXCLUDE (PUBYEAR,1991) OR EXCLUDE (PUBYEAR,1995) OR EXCLUDE (PUBYEAR,1996) OR EXCLUDE (PUBYEAR,1997) OR EXCLUDE (PUBYEAR,1998) OR EXCLUDE (PUBYEAR,1999))

The search was conducted on 18 May 2023 in two online databases; Web of Science (1885 hits) and Scopus (1190 hits). The searches were combined using mergeDBSources function in the bibliometrix package (Aria and Cuccurulllo 2017), giving a total of 1544 hits. It was subsequently noted that the keyword legume* had been excluded from the search. This was then added to the search string. By re-running the original string and using AND NOT those paper which specified legume* were added. After combining the WOK and the Scopus searches, this added 20 references. Sources were screened firstly on the basis of title and abstract, then secondly by scanning the full text. At each stage, sources were progressed unless it was apparent that an objective reason existed for it to be excluded from the study (exclusion rule). Sources were subsequently assessed for suitability. A total of 145 papers were assessed as sufficiently relevant for data extraction and inclusion in the review.

As a funder of organic projects, the Defra Research databases was searched for relevant projects. This added Smith et al 2018 to the information assessed. Organic Eprints - Welcome to Organic Eprints (orgprints.org) is a repository for results from Organic Projects. The results in OrgPrints for the QLIF and FertilCrop were extracted and assessed for relevance. This gave a total of nine and eleven papers respectively. In addition, relevant papers known to the authors that met the scope were also used to compile the review.

The REA has focused on assessing the direction of change and has not quantified absolute values.

8.1.2. Stakeholder Engagement

Aim

The aim of the stakeholder engagement was to gauge the level of knowledge and understanding across Scotland's agricultural industry stakeholders of the management practices commonly found on organic farms with reference to their impact on GHG emissions, both beneficial and not, and also their contribution to augmenting biodiversity on the land managed by farm businesses that undertake them.

To reach as wide a representation as possible of stakeholders in Scottish agriculture

To gather their opinions and views, evidence led or otherwise.

Approach

To ensure we were able to engage with farmers and the wider agricultural industry we held two stakeholder meetings.

- July 27th 2023, 12.30-2pm
- August 2nd 2023, 5-6.30pm

We compiled an internal list of industry representatives from our inventory of previous research studies performed for CXC and other organisations allied to Scotland's agriculture industry. This was augmented by crosschecking with the Agriculture and Rural Development (ARD) stakeholder group run by Scottish Government and stakeholder representatives were added as appropriate.

We augmented this list of industry representatives with commercial stakeholders across the supply chain including red meat processors, food service, auctioneers, large retailers, and small independent retailers.

We also drew upon our internal network of SRUC researchers, and SAC Consulting agricultural advisors with a range of experience of farming scenarios.

Both organic and conventional farmers were contacted through SOPA, and through the NFUS. In addition, we contacted all 8500+ subscribers to SAC Consulting's advisory service which is a direct reach to many farmers in Scotland.

Method of contact

The invitations to a choice of 2 x Zoom meetings were sent out 3 weeks prior to the first stakeholder engagement meeting in the following places:

- NFUS weekly newsletters for 2 weeks reaching all NFUS farming members and stakeholders.
- Social Media via SAC Consulting channels Twitter / FB.
- Direct mailing list of licensors of Scottish Organic Producers Association (SOPA).
- Direct invitation via internal mailing list of industry representatives, and SRUC / SAC personnel as outlined above.
- Included in SAC Consulting's subscriber publication Unearthed that reaches over 8500 farming businesses.

Method of engagement

We started the stakeholder engagement session with a brief overview of the project and an explicit explanation of what we wish attendees to do.

We used padlet boards and asked for comments on the benefits or disbenefits or each of 6 management practices for climate and biodiversity outcomes. We interspersed the time allowed for attendees to note comments with overarching discussion, without guiding their views, but adding information where appropriate.

We then picked up on gaps in commentary and asked attendees their views on why that was.

Management practices

- Reliance on legumes
- Using organic manures/bulky organic material
- Reduced synthetic inputs
- Integrating grazing in arable system
- Rotational/Mob grazing
- Minimum tillage
- Other

We asked for comments on the impact of organic farming using each particular practice on the following climate and nature outcomes. It was stressed that this was not a call to support organic farming more a call to unpick the impacts both good and bad on these outcomes.

- Reducing GHG emissions
- Soil Carbon storage
- Biodiversity
- Ability to deal with weather conditions, pests and diseases in 2045 .

Summary of the stakeholders involved in the online workshops

- 5 organic farmers
- 1 farmer with no organic land
- 4 advisors
- 8 industry representatives
- 1 charity representative
- 2 academics
- 4 “other”

8.2 REA results

Table A1 summarises the results of the REA. Based on the literature, the scores of 1, 0, -1 represent whether the organic management practices have a positive, neutral, or negative impact on the categories of GHGs, soil carbon, adaptation, and biodiversity. The confidence indicator gives an indication whether the body of the literature examined has a low, medium or high confidence of the likely outcome.

Table A1 Summarised results for organic management practices relative to conventional management practices for GHGs, soil carbon, adaptation potential and biodiversity

Management practice	Taxa	Biodiversity		Soil C		GHGs		Adaptation	
		Indicator	Confidence	Indicator	Confidence	Indicator	Confidence	Indicator	Confidence
Organic farming		1	Medium	1	High	1	Moderate	1	Medium
Rotation management		1	Low	1	Medium			0	
Organic FYM inputs				1	High			-1	Medium
Cover crop		1	Low	1	Medium				
Crop residues		1	Medium	1	Medium			1	Medium
Intraspecific crop diversification		0	Low					0	Medium
Intercropping (more than 2 species grown together)		0	Medium						
Tillage intensity				1	Medium				
Tillage frequency		0	Medium					-1	High
Flower strips		1	High					1	High
Organic weed management		1	High			-1	High		
Organic pest management		1	Medium					-1	Medium
Organic disease management		1	Medium					1	Medium
Legumes		1	Medium						
Biocontrol agents								1	Low
Rotation		1	Medium						

Management practice	Taxa	Biodiversity		Soil C		GHGs		Adaptation	
		Indicator	Confidence	Indicator	Confidence	Indicator	Confidence	Indicator	Confidence
Improving animal health						1	High		
Low/med stocking density during grazing		1	Medium						
Mid spp grazing						0	Low		
Good pasture management						1	Medium		
Slurry tank management						0			
Organic v conv livestock						-1	High		
Livestock integration		0	Low						
Cover crops	Decomposers	1	Low						
Livestock integration	Decomposers	0	Low						
Organic	Birds and mammals	0	Medium						
Organic	Arthropods general	1	Medium						
Organic	Decomposers	0	Low						
Organic	Plants	1	High						
Organic	Natural enemies	0	Low						
Organic	Pollinators	1	Medium						
Varietal mix	Decomposers	0	Low						
Varietal mix	All plants	0	Low						
Varietal mix	Arthropods general	0	Low						
Varietal mix	Natural enemies	0	Low						
Reduced tillage	Mammals	1	Low						

Management practice	Taxa	Biodiversity		Soil C		GHGs		Adaptation	
		Indicator	Confidence	Indicator	Confidence	Indicator	Confidence	Indicator	Confidence
Reduced tillage	Decomposers	0	Low						
Organic weed management	Birds and mammals	1	Low						
Organic weed management	Plants	1	Low						
Organic weed management	Decomposers	1	Low						
Organic disease management	Pollinators	1	Low						
Organic disease management	Natural enemies	1	Low						
Organic disease management	Decomposers	1	Low						
Organic pest management	Natural enemies	1	Low						
Organic pest management	Decomposers	1	Low						
No artificial fertilisers	Natural enemies	0	Low						
No artificial fertilisers	All plants	1	Low						
No artificial fertilisers	Seed eating arthropods	1	Low						

9 Glossary of Terms

GHGs	Greenhouse gas emissions (nitrous oxide, methane, carbon dioxide)
Intercropping	Intercropping (more than 2 species grown together)
Natural enemies	natural predators for the control of pests
Rapid Evidence Assessment (REA)	Rapid Evidence Assessment (REA) "provides a balanced assessment of what is known (and not known) in the scientific literature about an intervention, problem or practical issue by using a systematic methodology to search and critically appraise empirical studies." (Barends, et al. 2017)
Taxa	group of organisms

10 References

Aggestam, V., & Buick, J. (2017). A comparative analysis of vehicle-related greenhouse gas emissions between organic and conventional dairy production. *Journal of Dairy Research*, *84*(3), 360–369. https://doi.org/10.1017/S0022029917000322

Albrecht, H., Mademann, S., & Weikl, H. (2020). Development of the arable vegetation 23 years after conversion from conventional to organic farming-experiences from a farm-scale case study in southern Germany Entwicklung der Ackerwildkrautvegetation 23 Jahre nach der Umstellung auf ökologischen Landbau-Ergebnisse einer Fallstudie aus Süddeutschland. *Tuexenia*, *40*, 291–308. https://doi.org/10.14471/2020.40.005

Alvarez, R. (2022). Comparing Productivity of Organic and Conventional Farming Systems: A Quantitative Review. *Archives of Agronomy and Soil Science*, *68*(14), 1947–1958. https://doi.org/10.1080/03650340.2021.1946040

Are, M., Kaart, T., Selge, A., & Reintam, E. (2021). The effects of crops together with winter cover crops on the content of soil water-stable aggregates in organic farming. *Agriculture (Switzerland)*, *11*(11), 1035. https://doi.org/10.3390/agriculture11111035

Aria, M. & Cuccurulllo, C (2017) bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, 11, 959-975.

Armengot, L., Berner, A., Blanco-Moreno, J.M., Mäder, P., & Sans, F.X. (2015). Long-term feasibility of reduced tillage in organic farming. *Agronomy for Sustainable Development*, *35*(1), 339–346. https://doi.org/10.1007/s13593-014-0249-y

Autret, B., Beaudoin, N., Rakotovololona, L., Bertrand, M., Grandeau, G., Gréhan, E., Ferchaud, F. & Mary, B. (2019). Can alternative cropping systems mitigate nitrogen losses and improve GHG balance? Results from a 19-yr experiment in Northern France. *Geoderma*, *342*, 20–33. https://doi.org/10.1016/j.geoderma.2019.01.039.

Bareille, N., Duval, J., Experton, C., Ferchaud, S., Hellec, F. & Manoli, C. (2022). Animal health management concepts and practices in livestock production under organic farming specifications. *INRAE Prod. Anim.*, 35 (4), 357e-368e

Barends, E., Rousseau, D.M. & Briner, R.B. (Eds). (2017). CEBMa Guideline for Rapid Evidence Assessments in Management and Organizations, Version 1.0. Center for Evidence Based Management, Amsterdam. Available from www.cebma.org/guidelines/.

Barré, K., Le Viol, I., Julliard, R., Chiron, F. & Kerbiriou, C. (2018). Tillage and herbicide reduction mitigate the gap between conventional and organic farming effects on foraging activity of insectivorous bats. *Ecology and Evolution*, 8(3), 1496-1506.

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., & Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Global Change Biology*, *27*(19), 4697–4710. https://doi.org/10.1111/GCB.15747

Benaragama, D., Leeson, J.L., & Shirtliffe, S.J. (2019). Understanding the Long-Term Weed Community Dynamics in Organic and Conventional Crop Rotations Using the Principal Response Curve Method. *Weed Science*, *67*(2), 195–204. https://doi.org/10.1017/wsc.2018.64

Benton, T.G., Vickery, J.A. & Wilson, J.D. (2003). Farmland biodiversity: is habitat heterogeneity the key? *Trends in ecology & evolution*, 18(4), 182-188.

Biernat, L., Taube, F., Loges, R., Kluß, C. & Reinsch, T. (2020). Nitrous oxide emissions and methane uptake from organic and conventionally managed arable crop rotations on farms in Northwest Germany. *Sustainability (Switzerland)*, *12*(8). https://doi.org/10.3390/SU12083240

Birkhofer, K., Arvidsson, F., Ehlers, D., Mader, V.L., Bengtsson, J. & Smith, H.G. (2016). Organic farming affects the biological control of hemipteran pests and yields in spring barley independent of landscape complexity. *Landscape Ecology*, *31*(3), 567–579. https://doi.org/10.1007/s10980-015-0263-8

Birkhofer, K., Fließbach, A., Wise, D.H. & Scheu, S. (2008). Generalist predators in organically and conventionally managed grass-clover fields: Implications for conservation biological control. *Annals of Applied Biology*, *153*(2), 271–280. https://doi.org/10.1111/j.1744-7348.2008.00257.x

Boeraeve, F., Vialatte, A., Sirami, C., Caro, G., Thenard, J., Francis, F. & Dufrêne, M. (2022). Combining organic and conservation agriculture to restore biodiversity? Insights from innovative farms in Belgium and their impacts on carabids and spiders. *Frontiers in Sustainable Food Systems*, 6, 1003637.

Boinot, S. & Alignier, A. (2022). On the restoration of hedgerow ground vegetation: Local and landscape drivers of plant diversity and weed colonization. *Journal of Environmental Management*, 307, 114530.

Boldrini, A., Benincasa, P., Tosti, G., Tei, F. & Guiducci, M. (2007). Apparent N balance in organic and conventional low input cropping systems. 3rd QLIF Congress, Hohenheim, Germany, March 20-23, 2007. Archived at http://orgprints.org/view/projects/int_conf_qlif2007.html

Bos, J.F.F.P., De Haan, J.J., Sukkel, W. & Schils, R.L.M. (2007). Comparing energy use and greenhouse gas emissions in organic and conventional farming systems in the Netherlands. 3rd QLIF Congress, Hohenheim, Germany, pp. 1-4.

Brooker, R., Hewison, R., Karley, A.J., Mitchell, C., Neilson, R., Newton, A.C., Pakeman, R.J., Raubach, S., Shaw, S. & Verrall, S. (2023). SEAMS - Sustainability in Education and Agriculture Using Mixtures: Final Report. James Hutton Institute and the SEAMS partnership.

Caballero-López, B., Blanco-Moreno, J.M., Pérez-Hidalgo, N., Michelena-Saval, J.M., Pujade-Villar, J., Guerrieri, E., Sánchez-Espigares, J.A. & Sans, F.X. (2012). Weeds, aphids, and specialist parasitoids and predators benefit differently from organic and conventional cropping of winter cereals. *Journal of Pest Science*, *85*(1), 81–88. https://doi.org/10.1007/s10340-011-0409-7

Cabaret, J., Bouilhol, M. & Mage, C. (2002). Managing helminths of ruminants in organic farming. *Veterinary Research*, *33*(5), 625-640. https://doi.org/10.1051/vetres:2002043

Carrié, R., Ekroos, J. & Smith, H.G. (2022). Turnover and nestedness drive plant diversity benefits of organic farming from local to landscape scales. *Ecological Applications*, *32*(4), e2576.

Chabert, A. & Sarthou, J.-P. (2020). Conservation agriculture as a promising trade-off between conventional and organic agriculture in bundling ecosystem services. *Agriculture, Ecosystems & Environment*, *292*, 106815. https://doi.org/10.1016/j.agee.2019.106815

Chaloner, T.M., Gurr, S.J. & Bebber, D.P. (2021). Plant pathogen infection risk tracks global crop yields under climate change. *Nat. Clim. Chang.* 11, 710–715. https://doi.org/10.1038/s41558-021-01104-8

Chateil, C., Goldringer, I., Tarallo, L., Kerbiriou, C., Le Viol, I., Ponge, J.F., Salmon, S., Gachet, S. & Porcher, E. (2013). Crop genetic diversity benefits farmland biodiversity in cultivated fields. *Agriculture, Ecosystems & Environment*, 171, 25-32.

Chemlik, V., Šarapatka, B., Machac, O., Mikula, J., Laska, V. & Tuf, I.H. (2019). The effect of farming system and management practices on surface-dwelling soil macrofauna. *Zemdirbyste-Agriculture*, 106(4), 291–296.

Cole, L.J., Eory, V., Karley, A., Hawes, C., Walker, R.L. & Watson, C.A. (2021). The potential for an agroecological approach in Scotland: policy brief. Climate X Change. Available at: The potential for an agroecological approach in Scotland: policy brief (climatexchange.org.uk). [Accessed 15/05/2023].

Colombi, T., Walder, F., Büchi, L., Sommer, M., Liu, K., Six, J., van der Heijden, M.G.A., Charles, R. & Keller, T. (2019). On-farm study reveals positive relationship between gas transport capacity and organic carbon content in arable soil. *Soil*, *5*(1), 91–105. https://doi.org/10.5194/soil-5-91-2019

Córdoba, E.M., Chirinda, N., Li, F., & Olesen, J.E. (2018). Contributions from carbon and nitrogen in roots to closing the yield gap between conventional and organic cropping systems. *Soil Use and Management*, *34*(3), 335–342. https://doi.org/10.1111/SUM.12427

Dicks, L.V., Ashpole, J.E., Dänhardt, J., James, K., Jönsson, A., Randall, N., Showler, D.A., Smith, R.K., Turpie, S., Williams, D.R. & Sutherland, W.J. (2020) Farmland Conservation, in: W.J. Sutherland, L.V. Dicks, S.O. Petrovan & R.K. Smith (eds) *What Works in Conservation 2020*. Cambridge: Open Book Publishers. pp 283-321.

Dobben, Van, H.F., Quik, C., Wamelink, G.W. & Lantinga, E.A. (2019). Vegetation composition of Lolium perenne-dominated grasslands under organic and conventional farming. *Basic and Applied Ecology*, 36, 45-53.

Eory, V., Topp, K., Rees, B., Jones, S., Barnes, A., Smith, P., MacLeod, M. & Wall, E. (2023) Scenarios for emission reduction targets in Scottish agriculture. Climate X Change. Available at: Scenarios for emissions reduction targets in Scottish agriculture (climatexchange.org.uk). [Accessed 31/10/2023].

Emmerling, C. (2007). Reduced and conservation tillage effects on soil ecological properties in an organic farming system. *Biological Agriculture and Horticulture*, *24*(4), 363–377. https://doi.org/10.1080/01448765.2007.9755033

Eremeev, V., Talgre, L., Kuht, J., Mäeorg, E., Esmaeilzadeh-Salestani, K., Alaru, M., Loit, E., Runno-Paurson, E. & Luik, A. (2020). The soil microbial hydrolytic activity, content of nitrogen and organic carbon were enhanced by organic farming management using cover crops and composts in potato cultivation. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science*, *70*(1), 87–94. https://doi.org/10.1080/09064710.2019.1673475

Eyre M.D., Sanderson R.A., Shotton P.N. & Leifert C. (2009). Investigating the effects of crop type, fertility management and crop protection on the activity of beneficial invertebrates in an extensive farm management comparison trial. *Annals of Applied Biology*, 155, 267-276.

Eyre, M.D., Luff, M.L., Atlihan, R. & Leifert, C. (2012). Ground beetle species (Carabidae, Coleoptera) activity and richness in relation to crop type, fertility management and crop protection in a farm management comparison trial. *Annals of Applied Biology*, 161(2), 169-179.

Feber, R.E., Johnson, P.J., Firbank, L.G., Hopkins, A. & Macdonald, D.W. (2007). A comparison of butterfly populations on organically and conventionally managed farmland. *Journal of Zoology*, 273(1), 30-39.

Feber, R.E., Johnson, P.J., Bell, J.R., Chamberlain, D.E., Firbank, L.G., Fuller, R.J., Manley, W., Mathews, F., Norton, L.R., Townsend, M. & Macdonald, D.W. (2015). Organic farming: Biodiversity impacts can depend on dispersal characteristics and landscape context. *PLoS One*, 10(8), e0135921.

Feiziene, D., Feiza, V., Povilaitis, V., Putramentaite, A., Janusauskaite, D., Seibutis, V. & Slepetys, J. (2016). Soil sustainability changes in organic crop rotations with diverse crop species and the share of legumes. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, *66*(1), 36–51. https://doi.org/10.1080/09064710.2015.1063683

Fließbach, A., Oberholzer, H.-R., Gunst, L. & Mäder, P. (2007). Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. *Agriculture, Ecosystems & Environment*, *118*(1–4), 273–284. https://doi.org/10.1016/j.agee.2006.05.022

Fonderflick, J., Besnard, A., Chardès, M.C., Lanuzel, L., Thill, C. & Pointereau, P. (2020). Impacts of agricultural intensification on arable plants in extensive mixed crop-livestock systems. *Agriculture, Ecosystems & Environment*, 290, 106778.

Fontana, M., Berner, A., Mäder, P., Lamy, F. & Boivin, P. (2015). Soil Organic Carbon and Soil Bio-Physicochemical Properties as Co-Influenced by Tillage Treatment. *Soil Science Society of America Journal*, *79*(5), 1435–1445. https://doi.org/10.2136/sssaj2014.07.0288

Gabriel, D. & Tscharntke, T. (2007). Insect pollinated plants benefit from organic farming. *Agriculture, Ecosystems & Environment*, 118(1-4), 43-48.

Gabriel, D., Sait, S.M., Hodgson, J.A., Schmutz, U., Kunin, W.E. & Benton, T.G. (2010). Scale matters: the impact of organic farming on biodiversity at different spatial scales. *Ecology letters*, 13(7), 858-869.

Gallé, R., Happe, A.K., Baillod, A.B., Tscharntke, T. & Batáry, P. (2019). Landscape configuration, organic management, and within-field position drive functional diversity of spiders and carabids. *Journal of Applied Ecology*, 56(1), 63-72.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M., Smith, P., Scialabba, N.E.H. & Niggli, U. (2012). Enhanced top soil carbon stocks under organic farming. *Proceedings of the National Academy of Sciences of the United States of America*, 109(44), 18226–18231. https://doi.org/10.1073/PNAS.1209429109/-/DCSUPPLEMENTAL/SD01.XLSX

Geppert, C., Hass, A., Földesi, R., Donkó, B., Akter, A., Tscharntke, T. & Batáry, P. (2020). Agri-environment schemes enhance pollinator richness and abundance but bumblebee reproduction depends on field size. *Journal of Applied Ecology*, 57(9), 1818-1828.

Gibson, R.H., Pearce, S., Morris, R.J., Symondson, W.O.C. & Memmott, J. (2007). Plant diversity and land use under organic and conventional agriculture: a whole-farm approach. *Journal of Applied Ecology*, 44(4), 792-803.

Goulson, D., Lye, G.C. & Darvill, B. (2008). Decline and conservation of bumble bees. *Annual Review of Entomology*, 53, 191-208.

Gronle, A., Lux, G., Böhm, H., Schmidtke, K., Wild, M., Demmel, M., Brandhuber, R., Wilbois, K.-P. & Heß, J. (2015). Effect of ploughing depth and mechanical soil loading on soil physical properties, weed infestation, yield performance and grain quality in sole and intercrops of pea and oat in organic farming. *Soil and Tillage Research*, 148, 59–73. https://doi.org/10.1016/j.still.2014.12.004

Gross, A., Bromm, T., Polifka, S. & Schierhorn, F. (2022). The carbon footprint of milk during the conversion from conventional to organic production on a dairy farm in central Germany. *Agronomy for Sustainable Development*, *42*(3), 37. https://doi.org/10.1007/s13593-022-00775-7

Haas, G., Wetterich, F. & Köpke, U. (2001). Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. *Ecosystems and Environment*, *83*, 43–53.

Hance T. & Gregoirewibo C. (1987). Effect of agricultural practices on carabid populations. *Acta Phytopathologica Et Entomologica Hungarica*, 22, 147-160.

Happe, A.K., Riesch, F., Rösch, V., Gallé, R., Tscharntke, T. & Batáry, P. (2018). Small-scale agricultural landscapes and organic management support wild bee communities of cereal field boundaries. *Agriculture, Ecosystems & Environment*, 254, 92-98.

Hardman, C.J., Harrison, D.P., Shaw, P.J., Nevard, T.D., Hughes, B., Potts, S.G. & Norris, K. (2016). Supporting local diversity of habitats and species on farmland: a comparison of three wildlife-friendly schemes. *Journal of Applied Ecology*, 53(1), 171-180.

Heinze, S., Raupp, J. & Joergensen, R. G. (2010). Effects of fertilizer and spatial heterogeneity in soil pH on microbial biomass indices in a long-term field trial of organic agriculture. *Plant and Soil*, *328*(1–2), 203–215. https://doi.org/10.1007/s11104-009-0102-2

Henderson, I.G., Holland, J.M., Storkey, J., Lutman, P., Orson, J. & Simper, J. (2012). Effects of the proportion and spatial arrangement of un-cropped land on breeding bird abundance in arable rotations. *Journal of Applied Ecology*, 49(4), 883-891.

Hu, T., Sørensen, P. & Olesen, J. E. (2018). Soil carbon varies between different organic and conventional management schemes in arable agriculture. *European Journal of Agronomy*, *94*, 79–88. https://doi.org/10.1016/j.eja.2018.01.010

Hutton, S.A. & Giller, P.S. (2003). The effects of the intensification of agriculture on northern temperate dung beetle communities. *Journal of Applied Ecology*, 40(6), 994-1007.

Inclán, D.J., Cerretti, P., Gabriel, D., Benton, T.G., Sait, S.M., Kunin, W.E., Gillespie, M.A.K. & Marini, L. (2015). Organic farming enhances parasitoid diversity at the local and landscape scales. *Journal of Applied Ecology*, *52*(4), 1102–1109. https://doi.org/10.1111/1365-2664.12457

Johnson, K.H., Vogt, K.A., Clark, H.J., Schmitz, O. J. & Vogt, D.J. (1996). Biodiversity and the productivity and stability of ecosystems. *Trends in Ecology & Evolution*, 11(9), 372–377. https://doi.org/10.1016/0169-5347(96)10040-9

Jordon, M.W., Willis, K.J., Bürkner, P.C., Haddaway, N.R., Smith, P. & Petrokofsky, G. (2022). Temperate Regenerative Agriculture practices increase soil carbon but not crop yield—a meta-analysis. *Environmental Research Letters*, 17(9), 093001. https://doi.org/10.1088/1748-9326/ac8609

Junge, S.M., Storch, J., Finckh, M.R. & Schmidt, J.H. (2020). Developing Organic Minimum Tillage Farming Systems for Central and Northern European Conditions. In: Y. Dang, R. Dalal, N. Menzies (eds). No-till Farming Systems for Sustainable Agriculture. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-030-46409-7_11.

Kauer, K., Pärnpuu, S., Talgre, L., Eremeev, V. & Luik, A. (2021). Soil particulate and mineral-associated organic matter increases in organic farming under cover cropping and manure addition. *Agriculture (Switzerland)*, *11*(9), 903. https://doi.org/10.3390/agriculture11090903

Kaurin, A., Mihelič, R., Kastelec, D., Grčman, H., Bru, D., Philippot, L. & Suhadolc, M. (2018). Resilience of bacteria, archaea, fungi and N-cycling microbial guilds under plough and conservation tillage, to agricultural drought. *Soil Biology and Biochemistry*, *120*, 233–245. https://doi.org/10.1016/J.SOILBIO.2018.02.007

Kiefer, L., Menzel, F. & Bahrs, E. (2014). The effect of feed demand on greenhouse gas emissions and farm profitability for organic and conventional dairy farms. *Journal of Dairy Science*, *97*(12), 7564–7574. https://doi.org/10.3168/jds.2014-8284

Kirchmann, H. (2019). Why organic farming is not the way forward. *Outlook on Agriculture*, *48*(1), 22–27. https://doi.org/10.1177/0030727019831702/ASSET/IMAGES/LARGE/10.1177_0030727019831702-FIG3.JPEG

Kleijn, D. & Raemakers, I. (2008). A retrospective analysis of pollen host plant use by stable and declining bumble bee species. *Ecology*, 89(7), 1811-1823.

Knudsen, M.T., Meyer-Aurich, A., Olesen, J.E., Chirinda, N. & Hermansen, J. E. (2014). Carbon footprints of crops from organic and conventional arable crop rotations – using a life cycle assessment approach. *Journal of Cleaner Production*, *64*, 609–618. https://doi.org/10.1016/j.jclepro.2013.07.009

Koch B. & Meister E. (2000) Graded management intensity of grassland systems for enhancing floristic diversity. In: D. Gagnaux & J. R. Poffet (eds) *Livestock farming systems: integrating animal science advances in the search of sustainability. Proceedings of the fifth international symposium on livestock farming systems, Posieux, Fribourg, Switzerland, 19-20 August, 1999* (pp. 176-178). Wageningen Pers.

Krause, H.-M., Stehle, B., Mayer, J., Mayer, M., Steffens, M., Mäder, P. & Fliessbach, A. (2022). Biological soil quality and soil organic carbon change in biodynamic, organic, and conventional farming systems after 42 years. *Agronomy for Sustainable Development*, 42, 117. https://doi.org/10.1007/s13593-022-00843-y

Krauss, M., Ruser, R., Müller, T., Hansen, S., Mäder, P. & Gattinger, A. (2017). Impact of reduced tillage on greenhouse gas emissions and soil carbon stocks in an organic grass-clover ley - winter wheat cropping sequence. *Agriculture, Ecosystems & Environment*, 239, 324–333. https://doi.org/10.1016/j.agee.2017.01.029

Krauss, M., Wiesmeier, M., Don, A., Cuperus, F., Gattinger, A., Gruber, S., Haagsma, W.K., Peigné, J., Palazzoli, M.C., Schulz, F., van der Heijden, M.G.A., Vincent-Caboud, L., Wittwer, R.A., Zikeli, S. & Steffens, M. (2022). Reduced tillage in organic farming affects soil organic carbon stocks in temperate Europe. *Soil and Tillage Research*, 216, 105262. https://doi.org/10.1016/J.STILL.2021.105262

Krey, K.L., Blubaugh, C.K., Van Leuven, J.T. & Snyder, W.E. (2019). Organic Soils Control Beetle Survival While Competitors Limit Aphid Population Growth. *Environmental Entomology*, *48*(6), 1323–1330. https://doi.org/10.1093/ee/nvz100

Kromp B. (1999) Carabid beetles in sustainable agriculture: a review on pest control efficacy, cultivation impacts and enhancement. *Agriculture, Ecosystems & Environment*, 74, 187-228.

Kruse, M., Stein-Bachinger, K., Gottwald, F., Schmidt, E. & Heinken, T. (2016). Influence of grassland management on the biodiversity of plants and butterflies on organic suckler cow farms. *Tuexenia*, *36*, 97-119.

Kuht, J., Eremeev, V., Talgre, L., Madsen, H., Toom, M., Mäeorg, E. & Luik, A. (2016). Soil weed seed bank and factors influencing the number of weeds at the end of conversion period to organic production. *Agronomy Research*, *14*(4), 1372–1379.

Legzdiņa, L., Bleidere, M., Piliksere, D., & Ločmele, I. (2022). Agronomic Performance of Heterogeneous Spring Barley Populations Compared with Mixtures of Their Parents and Homogeneous Varieties. *Sustainability (Switzerland)*, *14*(15), 9697. https://doi.org/10.3390/su14159697

Leifeld, J. & Fuhrer, J. (2010). Organic Farming and Soil Carbon Sequestration: What Do We Really Know About the Benefits? *Ambio*, 39(8), 585–599. https://doi.org/10.1007/s13280-010-0082-8

Li, X., Petersen, S.O., Sørensen, P. & Olesen, J.E. (2015). Effects of contrasting catch crops on nitrogen availability and nitrous oxide emissions in an organic cropping system. *Agriculture, Ecosystems & Environment*, 199, 382–393. https://doi.org/10.1016/J.AGEE.2014.10.016

Litterick, A.; Harrier, L.; Wallace, P.; Watson, C.A. & Wood, M. (2003) Effects of composting manures and other organic wastes on soil processes and pest and disease interactions (CTE0203). Defra Final Report OF0313. Available at: Organic Eprints - Effects of composting manures and other organic wastes on soil processes and pest and disease interactions (orgprints.org). or Science Search (defra.gov.uk) (Accessed 15 August 2023)

Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P. & Niggli, U. (2002). Soil Fertility and Biodiversity in Organic Farming. *Science*, *296*(5573), 1694–1697. https://doi.org/10.1126/science.1071148

Madsen, H., Talgre, L., Eremeev, V., Alaru, M., Kauer, K. & Luik, A. (2016). Do green manures as winter cover crops impact the weediness and crop yield in an organic crop rotation? *Biological agriculture & horticulture*, *32*(3), 182-191.

Madsen, H., Talgre, L., Eremeev, V., Alaru, M., Maeorg, E. & Luik, A. (2017). Winter cover crops decrease weediness in organic cropping systems. In: *NJF Seminar 495-4th organic Conference: Organics for tomorrow's food systems, 19-21 June 2017, Mikkeli, Finland* (Vol. 13, No. 1, pp. 35-37).

Madsen, H., Talgre, L., Kuht, J., Alaru, M., Eremeev, V., Mäeorg, E., Loit, E. & Luik, A. (2020). Organic Cropping Systems do not Increase Weed Seed Numbers but do Increase Weed Diversity. *Agri Res & Tech: Open Access J*, 23(4), 44-51. https://doi.org/10.19080/ARTOAJ.2020.23.556244

Mangels J., Fiedler K., Schneider F.D. & Bluthgen N. (2017) Diversity and trait composition of moths respond to land-use intensification in grasslands: Generalists replace specialists. *Biodiversity and Conservation*, 26, 3385-3405.

Marja, R., Herzon, I., Viik, E., Elts, J., Mänd, M., Tscharntke, T. & Batáry, P. (2014). Environmentally friendly management as an intermediate strategy between organic and conventional agriculture to support biodiversity. *Biological Conservation*, 178, 146-154.

Marja, R., Viik, E., Mänd, M., Phillips, J., Klein, A.M. & Batáry, P. (2018). Crop rotation and agri-environment schemes determine bumblebee communities via flower resources. *Journal of Applied Ecology*, 55(4), 1714-1724.

Mcclelland, S.C., Paustian, K. & Schipanski, M.E. (2020). *Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis*. *Ecological Applications*, *31*(3), e02278. https://doi.org/10.1002/eap.2278

McCracken, D.I. (1993). The potential for avermectins to affect wildlife. *Veterinary parasitology*, 48(1-4), 273-280.

Mendes Costa, M., Cardo, M., Ruano, Z., Alho, A.M., Dinis-Teixeira, J., Aguiar, P. & Leite, A. (2023). Effectiveness of antimicrobial interventions directed at tackling antimicrobial resistance in animal production: A systematic review and meta-analysis. *Preventive Veterinary Medicine*, *218*, 106002. https://doi.org/10.1016/j.prevetmed.2023.106002

Metzke, M., Potthoff, M., Quintern, M., Heß, J. & Joergensen, R.G. (2007). Effect of reduced tillage systems on earthworm communities in a 6-year organic rotation. *European Journal of Soil Biology*, 43, S209-S215.

Moorcroft, D., Whittingham, M.J., Bradbury, R.B. & Wilson, J.D. (2002). The Selection of Stubble Fields by Wintering Granivorous Birds Reflects Vegetation Cover and Food Abundance. *Journal of Applied Ecology*, 39(3), 535–547. http://www.jstor.org/stable/827145

Morris, C.D. (2021). How Biodiversity-Friendly Is Regenerative Grazing? *Frontiers in Ecology and Evolution*, 9, 816374.

Muneret, L., Mitchell, M., Seufert, V., Aviron, S., Djoudi, E.A., Pétillon, J., Plantegenest, M., Thiéry, D. & Rusch, A. (2018). Evidence that organic farming promotes pest control. *Nature Sustainability*, *1*(7), 361–368. https://doi.org/10.1038/s41893-018-0102-4

Novak, S.M. & Fiorelli, J.L. (2011). Greenhouse Gases and Ammonia Emissions from Organic Mixed Crop-Dairy Systems: A Critical Review of Mitigation Options. In: E. Lichtfouse, M. Hamelin, M. Navarrete, P. Debaeke (eds) *Sustainable Agriculture Volume* 2. Dordrecht: Springer, pp.529-556. https://doi.org/10.1007/978-94-007-0394-0_24

Poeplau, C. & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment*, *200*, 33–41. https://doi.org/10.1016/j.agee.2014.10.024

Pelosi, C., Bertrand, M. & Roger-Estrade, J. (2009). Earthworm community in conventional, organic and direct seeding with living mulch cropping systems. *Agronomy for Sustainable Development*, 29, 287-295.

Pelosi, C., Bertrand, M., Thénard, J. & Mougin, C. (2015). Earthworms in a 15 years agricultural trial. *Applied Soil Ecology*, 88, 1-8.

Pélosi, C., Toutous, L., Chiron, F., Dubs, F., Hedde, M., Muratet, A., Ponge, J.F., Salmon, S. & Makowski, D. (2013). Reduction of pesticide use can increase earthworm populations in wheat crops in a European temperate region. *Agriculture, Ecosystems & Environment*, 181, 223-230.

Pfiffner, L. & Luka, H. (2003). Effects of low-input farming systems on carabids and epigeal spiders–a paired farm approach. *Basic and Applied Ecology*, 4(2), 117-127.

Pottier, E., Tournadre, H., Benoit, M. & Prache, S. (2009). Maximizing the share of grazing in the feeding of sheep: advantages for feed self-sufficiency, for the environment, and for the quality of the products. *Fourrages*, 199, 349-371.

Power, E.F., Jackson, Z. & Stout, J.C. (2016). Organic farming and landscape factors affect abundance and richness of hoverflies (Diptera, Syrphidae) in grasslands. *Insect Conservation and Diversity*, *9*(3), 244–253. https://doi.org/10.1111/ICAD.12163

Puech, C., Baudry, J., Joannon, A., Poggi, S. & Aviron, S. (2014). Organic vs. conventional farming dichotomy: Does it make sense for natural enemies? *Agriculture, Ecosystems & Environment*, 194, 48–57. https://doi.org/10.1016/J.AGEE.2014.05.002

Pugesgaard, S., Petersen, S.O., Chirinda, N. & Olesen, J.E. (2017). Crop residues as driver for N2O emissions from a sandy loam soil. *Agricultural and Forest Meteorology*, 233, 45–54. https://doi.org/10.1016/J.AGRFORMET.2016.11.007

Pulungan, M.A., Suzuki, S., Gavina, M.K.A., Tubay, J.M., Ito, H., Nii, M., Ichinose, G., Okabe, T., Ishida, A., Shiyomi, M. & Togashi, T. (2019). Grazing enhances species diversity in grassland communities. *Scientific Reports*, 9(1), 11201.

Reumaux, R., Chopin, P., Bergkvist, G., Watson, C. A. & Öborn, I. (2023). Land Parcel Identification System (LPIS) data allows identification of crop sequence patterns and diversity in organic and conventional farming systems. *European Journal of Agronomy*, 149, 126916. https://doi.org/10.1016/J.EJA.2023.126916

Rotchés-Ribalta, R., Sans, F.X., Mayer, J. & Mäder, P. (2020). Long-term farming systems and last crop sown shape the species and functional composition of the arable weed seed bank. *Applied Vegetation Science*, 23(3), 428-440.

Rundlöf, M., Edlund, M. & Smith, H.G. (2010). Organic farming at local and landscape scales benefits plant diversity. *Ecography*, 33(3), 514-522.

Rusch, A., Birkhofer, K., Bommarco, R., Smith, H.G. & Ekbom, B. (2014). Management intensity at field and landscape levels affects the structure of generalist predator communities. *Oecologia*, 175, 971-983.

Sands, B. & Noll, M. (2022). Toxicity of ivermectin residues in aged farmyard manure to terrestrial and freshwater invertebrates. *Insect Conservation and Diversity*, 15(1), 9-18.

Schumacher, M., Ohnmacht, S., Rosenstein, R. & Gerhards, R. (2018). How Management Factors Influence Weed Communities of Cereals, Their Diversity and Endangered Weed Species in Central Europe. *Agriculture*, 8(11), 172. https://doi.org/10.3390/AGRICULTURE8110172

Seipel, T., Ishaq, S.L., Larson, C. & Menalled, F.D. (2022). Weed Communities in Winter Wheat: Responses to Cropping Systems under Different Climatic Conditions. *Sustainability (Switzerland)*, *14*(11), 6880. https://doi.org/10.3390/su14116880

Sereda, E., Wolters, V. & Birkhofer, K. (2015). Addition of crop residues affects a detritus-based food chain depending on litter type and farming system. *Basic and Applied Ecology*, *16*, 746–754. https://doi.org/10.1016/j.baae.2015.07.005

Sidauruk, L. & Sipayung, P. (2018). Cropping management on potato field, a strategy to suppress pest by increasing insect diversity and natural enemies. *IOP Conference Series: Earth and Environmental Science*, *205*(1), 012026. https://doi.org/10.1088/1755-1315/205/1/012026

Sidemo-Holm, W., Carrié, R., Ekroos, J., Lindström, S.A. & Smith, H.G. (2021). Reduced crop density increases floral resources to pollinators without affecting crop yield in organic and conventional fields. *Journal of Applied Ecology*, 58(7), 1421-1430.

Skinner, C., Gattinger, A., Krauss, M., Krause, H.-M., Mayer, J., van der Heijden, M.G.A. & Mäder, P. (2019). The impact of long-term organic farming on soil-derived greenhouse gas emissions. *Scientific Reports*, *9*(1), 1702. https://doi.org/10.1038/s41598-018-38207-w

Skuce, P.J., Morgan, E.R., van Dijk, J. & Mitchell, M. (2013). Animal health aspects of adaptation to climate change: beating the heat and parasites in a warming Europe. *Animal*, 7(s2), 333–345.

Smith, L.G., Williams, A.G. & Pearce, B.D. (2015). The energy efficiency of organic agriculture: A review. *Renewable Agriculture and Food Systems*, *30*(3), 280–301. https://doi.org/10.1017/S1742170513000471

Smith, L., Egan, J., Woolford, A., Orsini, S., Mullender, S. & Padel S. (2018) Reviewing Opportunities, Barriers and Constraints for Organic Management Techniques to Improve Sustainability of Conventional Farming. Defra Final Report OF03111. Available at: Science Search (defra.gov.uk) (Accessed 15 August 2023).

Smith, L.G., Kirk, G.J.D., Jones, P.J. & Williams, A.G. (2019). The greenhouse gas impacts of converting food production in England and Wales to organic methods. *Nature Communications*, 10(1), 1–10. https://doi.org/10.1038/s41467-019-12622-7

Sosulski, T., Srivastava, A.K., Ahrends, H.E., Smreczak, B. & Szymańska, M. (2023). Carbon Storage Potential and Carbon Dioxide Emissions from Mineral-Fertilized and Manured Soil. *Applied Sciences (Switzerland)*, *13*(7). https://doi.org/10.3390/app13074620

Steinberg, G. & Gurr, S.J. (2020). Fungi, fungicide discovery and global food security. *Fungal Genet Biol*, 144, 103476. https://doi.org/10.1016/j.fgb.2020.103476.

Stockdale, E.A., Lampkin, N.H., Hovi, M., Keatinge, R., Lennartsson, E.K.M., Macdonald, D.W., Padel, S., Tattersall, F.H., Wolfe, M.S. & Watson, C.A. (2001). Agronomic and environmental implications of organic farming systems. *Advances in Agronomy*, *70*, 261–327. https://doi.org/10.1016/S0065-2113(01)70007-7

Sun, H.Y., Koal, P., Gerl, G., Schroll, R., Joergensen, R.G. & Munch, J.C. (2017). Water-extractable organic matter and its fluorescence fractions in response to minimum tillage and organic farming in a Cambisol. *Chemical and Biological Technologies in Agriculture*, *4*(1), 1-11. https://doi.org/10.1186/s40538-017-0097-5

Szostek, M., Szpunar-Krok, E., Pawlak, R., Stanek-Tarkowska, J. & Ilek, A. (2022). Effect of Different Tillage Systems on Soil Organic Carbon and Enzymatic Activity. *Agronomy*, *12*(1), 208. https://doi.org/10.3390/agronomy12010208

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman, M. & Hallin, S. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances*, *6*(45), eaba1715. https://doi.org/10.1126/SCIADV.ABA1715/SUPPL_FILE/ABA1715_SM.PDF

Timberlake, T.P., Vaughan, I.P. & Memmott, J. (2019). Phenology of farmland floral resources reveals seasonal gaps in nectar availability for bumblebees. *Journal of Applied Ecology*, 56(7), 1585-1596.

Török, E., Zieger, S., Rosenthal, J., Földesi, R., Gallé, R., Tscharntke, T. & Batáry, P. (2021). Organic farming supports lower pest infestation, but less natural enemies than flower strips. *Journal of Applied Ecology*, *58*(10), 2277–2286. https://doi.org/10.1111/1365-2664.13946

Tscharntke, T., Grass, I., Wanger, T.C., Westphal, C. & Batáry, P. (2021). Beyond organic farming–harnessing biodiversity-friendly landscapes. *Trends in Ecology & Evolution*, 36(10), 919-930.

Ulber, L., Steinmann, H., Klimek, S. & Isselstein, J. (2009). An on-farm approach to investigate the impact of diversified crop rotations on weed species richness and composition in winter wheat. *Weed Research*, 49(5), 534–543. https://doi.org/10.1111/j.1365-3180.2009.00722.x

Watson, C.A., Atkinson, D., Gosling, P., Jackson, L.R. & Rayns, F.W. (2006). Managing soil fertility in organic farming systems. *Soil Use and Management*, 18, 239–247. https://doi.org/10.1111/J.1475-2743.2002.TB00265.X

Watson, C.A., Reckling, M., Preissel, S., Bachinger, J., Bergkvist, G., Kuhlman, T., Lindström, K., Nemecek, T., Topp, C.F.E., Vanhatalo, A., Zander, P., Murphy-Bokern, D., & Stoddard, F.L. (2017). Grain Legume Production and Use in European Agricultural Systems. In: *Advances in Agronomy*, 144, 235–303. https://doi.org/10.1016/bs.agron.2017.03.003.

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