

The influence of regenerative farming practices on malting barley and wheat grain-quality: A systematic literature-review

Kenneth Loades[1] (kenneth.loades@hutton.ac.uk), David Boldrin[1]

Zach Reilly[2], Eric Anderson[3], Tim George[1], Tracy Valentine[1]

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Executive Summary

The Scotch Whisky Association (SWA) aims to fully decarbonise their operations by 2040 and drive their full emissions profile down as far and fast as possible. The goal is in achieving net zero emissions across all scopes by 2045 through collaboration with supply chain partners and regulators. With Scope 3 emissions representing over 80% of emissions across the industry, maximising opportunities associated with regenerative practices offers a significant opportunity requiring support through supply chains, in research, and across governments.

In 2026, the adoption of regenerative agriculture is shifting from broad ambition to measurable outcomes, characterised by deeper evidence regarding its impact on spring barley. Regenerative agriculture comprises of five principles 1) minimal soil disturbance; 2) keeping the soil surface covered; 3) keeping living roots in the soil; 4) Growing a range of crops; 5) Bringing grazing animals back to the land. While practices underpinning these principles like cover cropping and reduced tillage may offer long-term resilience, they introduce specific challenges for yield and quality during the transition phase. Transitioning to regenerative systems can lead to an initial yield drop of 10% to 25% for cereal crops. After this transition period of 3 to 6 years, yields typically stabilise or improve as ecosystem functions and soil health enhance.

The uptake of regenerative agricultural principles in Scotland is not documented, therefore, the extent and information on the adoption of practices implemented on farm is largely unknown. Nevertheless, regenerative principles are often discussed within farmer groups or levy boards in addition to discussions between advisors and farmers, either in isolation or in combination with general integrated crop management approaches. There are a limited number of studies on the causal relationship between the five core-principles of regenerative agriculture (**Table 1**) and grain quality in barley and wheat. Such information is critical in understanding potential trade-offs, or opportunities, to further support practices that both enhance ecosystem service and function whilst also increase or maintain quality. It is acknowledged that data may exist within the barley and wheat sector which is not openly accessible. Should such data on grain quality and agronomic practice be made available, a better understanding of relationships between practice and quality could be made. Funded research council or Horizon Europe projects may also hold valuable data which has not yet been published (for example the Sustainability in Education and Agriculture using Mixtures (SEAMS)) highlighting other potential sources. Other data repositories (such as Zenodo) may hold valuable information, however, analysis of unpublished data was beyond the scope of the project.

Although in recent years there has been a shift in farmers perception of regenerative agriculture, there remains significant challenges which require addressing before these practises become mainstream. The most major of which is robust data to demonstrate that the adoption of regenerative agricultural practises will improve yield, quality and resilience on farm. Such information will contribute towards increasing farmer confidence in the adoption of regenerative practices and therefore derisking issues around uptake. With this in mind, targeted research and industry financial support is urgently needed to adopt agricultural strategies and agronomic practices able to maintain grain-quality while tackling environmental impacts and scope-three emissions throughout the supply chain.

Following the systematic review of scientific literature, including expert input from independent agronomists, key areas were highlighted where more research and understanding is required. The following list summarises these key research needs:

- Understanding nutrient release and availability from cover crops and green manures
- Impact of non-cash crop destruction techniques on timings of nutrient release relative to crop growth stage and the effects on cereal grain quality
- Impact of different cover crop mixes on nutrient status and release
- The role of livestock in grazing winter cereals and impact on grain quality driven by potential nutrient availability
- Impact of different direct drill systems on establishment success through changing tillage practices
- Understanding the link between regenerative practices and soil water variability under changing rainfall intensity which may impact yield and quality
- Impact of regenerative practices on soil moisture status (for example under drought conditions) over the growing season
- Cultivar performance screening under different tillage systems and organic inputs
- Optimising winter barley varieties for malting characteristics and optimisation within a regenerative system
- Impacts associated with changes in tillage practice and underlying soil properties, such as texture and impacts through the soil profile
- Weed management strategies under reduced tillage
- Quantification of impact on gross margin of production, yield, and quality during the transition towards more regenerative practices (such as tillage)
- Soil moisture monitoring to contribute to data driven management (precision agriculture) to minimise traffic during sub-optimal conditions
- Understanding risks to grain quality associated with the application of organic inputs (e.g. heavy metals in slurry or plastics/microplastics in composts)

Table 1. Summary of the impact regenerative agriculture has on grain yield and quality

Minimise soil disturbance	Keep the soil-surface covered	Keep living roots in the soil	Grow a diverse range of crops	Bringing grazing animals back to the land
"yield gap" in the transition period between ploughing and no-tillage	66% of the arable land in Scotland left bare overwinter	Grain N concentration increased with increasing N supply from grass–clover pre-crop	Diversified cropping-systems increase wheat yield, yield stability and sustainability	Barley following a grazing-crop (oat) established using no-till practice, had lower screenings than barley following a grazing-crop established in a plough system
Tillage practice can affect grain yield and quality with inconsistencies in findings	Catch crops did not significantly affect cereal grain yield and reduced grain N concentration (single study)	Adoption of winter barley requires a change in market demand	Crop mixture can have positive indirect effects on grain quality by influencing the severity of pests and diseases	Higher grain N concentration with cattle-manure compared to pig-manure

Reducing soil tillage can increase disease	Opportunity to adapt rotations to improve soil cover is largely limited by market demand			
Small number of studies make it difficult to reach robust conclusions	Understanding the nitrogen carry through is essential			
Variability in results likely dependent on soil types and climate conditions between studies.				

The key research recommendations were selected based on both findings and expert opinion for each of the 5 currently recognised regenerative agriculture practices:

Minimise soil disturbance

- Although scientific evidence shows that tillage can affect grain yield and quality, there are inconsistencies in findings.
- A "yield gap" in the transition period between ploughing and both no-tillage and reduced tillage is well recognised. In England, farmers have been able to access support to move towards reduced tillage systems (FETF Grant), however, no such support is available in Scotland at present.
- Contrasting results and a lack of clear effects within the scientific literature could be explained by the influence of different soil types and climate conditions between studies.
- Reducing soil tillage can increase the frequency of Fusarium head blight and mycotoxins contamination in grain, whereas it was decreased by ploughing (see Champeil et al. 2004).
- Rotational crops such as potatoes or vegetables can impact soil health improvements from reduced tillage within a single season.
- In general, the small number of studies make it difficult to reach robust conclusions.

Keep the soil-surface covered

- There are two main strategies to create permanent ground cover in Scotland: rotation and cover cropping.
- An estimated 66% of the arable land in Scotland left bare overwinter.
- Cover cropping presents several challenges in Scotland. The most significant is the seasonal opportunity to establish cover crops.
- The degree of change in grain quality, and its significance, often depended on the regenerative practice. For example, in milling wheat, grain N was found to decrease under regenerative practices (negative impact) however this would be perceived as being beneficial in malting wheat.

- The limited number of studies investigating the relation between “soil-improving non-cash crops” and grain quality, and the wider variety of “non-cash crops” treatments, do not allow to derive robust conclusions.
- The opportunity to adapt rotations to improve soil cover is largely limited by market demand.
- Cover crops provide limited opportunity within Scotland unless they are incentivised or new mixtures become available. Cover crops will also need to be accompanied by an adaptation in the cropping rotation.
- Understanding the nitrogen carry through is essential for planning fertiliser requirements and ensuring malting barley grown after cover crops meets market specifications.
- Some growers suggest that cover crops also negatively affect the workability of the soil in the spring.

Keep living roots in the soil

- Aligned to keeping the soil-surface covered, rotations should include more autumn cropping to maintain living roots in soil
- Inclusion of grassland within an arable rotation requires a significant systems change and the development of a local market for grass. Moreover, intensively farmed grassland can introduce unintended consequences such as soil compaction from heavy silage making machinery, and the removal of high quantities of soil potassium reserves.
- Wide adoption of winter barley requires a change in market demand, but winter barley with good malting quality could be selected or bred.
- Grain N concentration increased with increasing N supply from the grass–clover pre-crop. The slower mineralisation of the organic matter in the grass–clover probably increased late season N uptake.

Grow a diverse range of crops

- Both above and below ground biodiversity is acknowledged to deliver multiple benefits however there is a need to understand how best to define this
- Most of the Scottish arable land falls within the classification 3.2, which is capable of average production.
- Diverse crop rotation may include potatoes, brassicas and carrots, but these crops are intensive and are typically perceived to be detrimental to soil health.
- Crop diversity largely varies by region.
- A major challenge to intercropping is the control of weeds due to the lack of selective herbicides which are safe to use on both crops (e.g., peas and spring barley).
- Mixing peas and spring barley can have multiple benefits including structural stability of the bi-crop and the complementary of root systems.
- Diversified cropping-systems increase wheat yield, yield stability and sustainability.
- Crop mixture can have positive indirect effects on grain quality by influencing the severity of pests and diseases.
- While the environmental and yield-stability benefices of crop-diversification are well recognised, more work is needed in the case of grain quality.

Bringing grazing animals back to the land

- Increasing interest from arable farmers who would like to integrate livestock by grazing cover crops or grazing winter cereals.
- Manures provides an organic amendment which can have significant influences (positive and negative) on soil health and grain yield and quality.
- Barley following a grazing-crop (oat) established using no-till practice, had lower screenings than barley following a grazing-crop established in a plough system.
- Higher grain N concentration with cattle-manure compared to pig-manure revealed different N supply dynamics between the two manures.
- An increase in livestock numbers will have knock-on effects in terms of total emissions and other environmental externalities.

Background and Rationale

Regenerative agriculture is gaining attention as a systems approach to reducing environmental impacts while enhancing soil health, biodiversity, and farm resilience. Regenerative agriculture is based on five principles (1. Minimise soil disturbance; 2. Keep the soil-surface covered; 3. Keep living roots in the soil; 4. Grow a diverse range of crops; 5. Bring grazing animals back to the land; **Figure 1**) and is underpinned by several different practices such as no-tillage and cover crops. It should also be recognised that despite the term "regenerative agriculture" becoming popular in recent years, its objectives and principles are shared by several agricultural systems from alternative to conventional, such as organic agriculture, conservation agriculture and agroecology. In this report, we will use the term "regenerative practices" for all practices underpinning the five principles of regenerative agriculture or any agroecological practices aiming to reduce agricultural environmental impact. While research has focused on environmental sustainability and productivity, of these alternative practices, evidence on their influence on grain quality - particularly for malting barley and wheat - remain fragmented. This is particularly important for Scotland's malting barley and wheat sectors, which requires consistent grain quality to meet industry specifications. Therefore, understanding whether regenerative practices maintain, enhance, or compromise quality traits is critical for grower adoption and supply chain confidence.

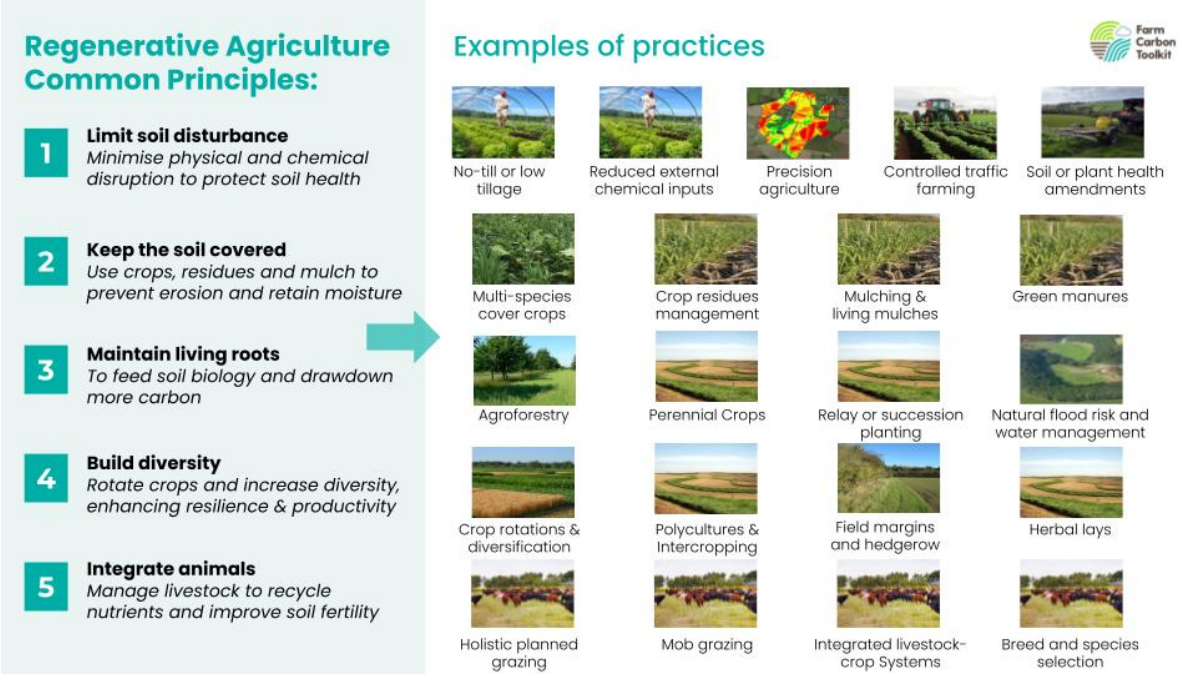


Figure 1. Regenerative agriculture principles from Farm Carbon Toolkit

Aim of the review

The aim of this combined literature review and expert opinion report is to identify, collate, and describe relevant published research (peer reviewed sources) and grey literature focusing on the influence of regenerative practices on barley and wheat grain-quality within the Scottish context and under climatically comparable conditions.

The scope of this research is as follows: field-studies and metanalyses investigating relationships between regenerative-farming practices (e.g. no-tillage, crop diversification, cover crops) on grain-quality (screening, protein concentration etc) of malting barley and wheat within the Scottish context or climatically comparable conditions. This review will not include the following: laboratory studies, greenhouse and pot experiments, modelling studies without measured field data, and opinion pieces.

Primary question

Primary question: "*What are the effects of regenerative farming-practices on the grain-quality of malting barley and wheat grown in Scotland?*"

The primary question is framed using population (P), interventions (I), comparators (C) and outcomes (O) key elements (**Table 2**).

Table 2. Component descriptors of the population (P), interventions (I), comparators (C) and outcomes (O) (PICO) approach used in the review

Population	**Geography**: Studies conducted in Scotland OR regions with climatically similar conditions defined as: ➢ Köppen climate classification Cfb (cool temperate, maritime) ➢ Mean annual temperature 7–11°C, annual rainfall 600–1400 mm ➢ Similar growing season length (e.g., Ireland, Northern England, parts of Scandinavia, New Zealand and Canada) ➢ Crops: barley and wheat.
Interventions	**Regenerative Practices** ○ Reduced, minimum, strip or zero tillage ○ Cover cropping, living mulches or catch cropping ○ Diverse crop rotations ○ Reduced synthetic fertiliser and/or pesticide inputs ○ Integration of livestock (e.g., mob grazing, manure cycling) ○ Organic or agroecological approaches Systems self-identifying as "regenerative agriculture," "conservation agriculture," or "agroecological" will be included if practices are clearly described.
Comparators	Conventional or standard regional practice (e.g., plough-based tillage, monoculture or simple rotation, standard fertiliser/pesticide regimes), or temporal comparisons (pre- vs post-adoption of regenerative practices on the same farm/field).
Outcomes	**Primary outcomes** (grain quality): Malting barley: Grain nitrogen content, germination energy, diastatic power, extract yield, predicted spirit yield, β-glucan, grain size/screenings, thousand grain weight, specific weight, grain density, hot water extract, wort viscosity mycotoxins (DON), grain skinning, grain splitting Wheat: Grain protein content, gluten strength/index, Hagberg falling number, test weight, milling yield, alcohol yield, variety group (endosperm texture), N content, hardness, viscosity, protein content.

	Secondary outcomes: Grain yield (t/ha), nitrogen use efficiency, soil health indicators linked to quality (e.g., soil N supply), disease pressure affecting quality, carbon sequestration in soils.

Publication types

- **Peer-reviewed** journal articles and conference papers.
- **Grey literature** with scientific rigor: government and levy body reports (e.g., AHDB, SASA, Teagasc), university theses and dissertations, research institute reports with clear methods and primary data.

A full description of the methos employed in this review may be found in **Appendix 1**.

Key findings for each of the 5 regenerative practices investigated

1. Minimise soil disturbance

Expert opinion

Scottish cropping systems are dominated by the inversion plough, where soil is inverted annually to a depth of 20-30 cm. The depth of ploughing, and therefore the amount of soil disturbance, is driven by the planned crop (potatoes and root crops are generally ploughed to a greater depth) and the soil type (depth of topsoil). In recent years, there has been an increase in the non-inversion establishment of some crops, particularly oilseed rape. Strip tillage - where the soil is worked to a similar depth as the plough but not inverted – has become increasingly popular due to the higher work rate (area cultivated per unit of time) associated with inversion-based systems. Some growers have used a non-inversion system for oilseed rape for several years and expanded this practice to include a range of winter crops, including winter wheat, winter oats and winter barley. Although some early adopters of a more regenerative approach use reduced and minimum tillage for a range of crops, even the most enthusiastic farmers struggle to establish a spring barley crop with sufficient tillers, in a direct drill or non-inversion scenario.

Soil cultivation is essential to producing high yielding crops of spring barley. The crop has a short growing season and benefits from the mineralised nitrogen from cultivation, alongside consistent seed to soil contact - both factors key in the development of suitable ear and grain number. Mechanical disturbance can also influence the aerobic capacity of the soil, leading to temporary changes in pH and phosphate availability. Both pH and phosphate are crucial for spring barley crops which are not tolerant of acidic soil and require phosphate in soil solution to promote root development, driving canopy development and yield.

Table 3. Challenges and opportunities for minimising soil disturbance

Challenges to minimising soil disturbance	**Opportunities from minimising soil disturbance**
Inability to rectify soil compaction if damage occurs (for example from a wet harvest).	Increased work rates resulting from fewer cultivation passes.
Uneven sowing depth and poor seed to soil contact, resulting from an uneven seed bed.	Lower establishment costs on an area basis as number of cultivation passes are reduced.
Requirement for additional equipment with associated capital cost.	Reduced emissions from fuel use arising from less soil movement.
Additional plant protection products required to control weeds, pests and disease.	Reduction in common eyespot disease.
Increase in rhyncosporium, net blotch, ramularia, leaf stripe, sharp eyespot and fusarium diseases, potentially reducing yields and quality.	Increase in soil surface protection from trash and straw accumulation, leading to reduced soil and water erosion events.

Lack of temporal and spatial consistency for grain yield and quality leading to variation in carbon footprint.	

Scientific literature (Tables 3 and 8)

The systematic review of scientific literature returned fourteen documents on reduced tillage and grain quality in barley and wheat. These manuscripts, published between 1993 and 2025, investigated several quality parameters including mineral concentration in grain, grain N and grain proteins. **Although scientific evidence shows that tillage can affect grain yield and quality, there are inconsistencies in findings**. In particular, the effect of reduced tillage is dependent on climate conditions with beneficial effects accomplished through the preservation of soil moisture during dry periods (Malhi and Lemke 2007). Moreover, positive effects were generally recorded after an initial yield penalty following the adoption of no-tillage practices. For example, Soon and Clayton 2002 reported that during the second rotation wheat yield increased by 22% in a no-tillage system, following a yield drop during the first rotation. This is now r**ecognised** as **"yield gap" in the transition period between ploughing and no-tillage**. Reducing tillage has also shown to influence macro- and micro-nutrients uptake and grain-concentrations (Carter and Gupta 1997; Gao and Grant 2011, 2012; Malhi and Lemke 2007). However, results on nutrient uptake and concentrations in grain did not show strong and consistent trends. Results from McConkey et al. (2002) suggested lower N availability under a no-tillage approach whilst Malhi and Lemke (2007) reported greater N in barley grain under no-tillage in respect to conventional tillage. Micronutrients such as Cu, Zn, Mn and Fe showed a reduction under reduced tillage (shallow tillage and direct drilling) compared to ploughing. In contrast, a study by Gao and Grant (2011) on the influence of tillage on grain quality in wheat, suggested that reduced tillage practices have little influence on mineral concentration in grain. **Contrasting results and a lack of clear effects within the scientific literature could be explained by the effect of different soil types and climate conditions between studies**. For instance, no-tillage showed positive effects on moisture retention in fine-texture soils, but no effect on sandy soil (McConkey et al. 1996).

Beyond specific grain quality, possible trade-offs between reduced tillage and crop disease should also be considered. For instance, **reducing soil tillage increased the frequency of Fusarium head blight and mycotoxins contamination in grain, whereas it was decreased by ploughing** (Champeil et al. 2004). In general, the **small number of studies make it difficult to reach robust conclusions** from the scientific literature on the interaction between climate, soil time, tillage practice and grain quality.

Challenges and opportunities

Within Scotland there are significant opportunities to increase the area of land managed with minimal soil disturbance, however, this change presents many challenges in practice. The most adaptable crops to establish with reduced tillage methods are oilseed rape or field beans, crops which thrive on wide row spacing and have sufficient rooting structures to compensate for reduced cultivations. A major challenge to practice change at present is the unknown and unquantified yield

reduction associated with moving from conventional to reduced disturbance establishment systems in Scotland. One factor contributing to this knowledge gap is the lack of suitable trialling methods on small plots, as trial machinery is largely limited in its cultivation type. To accurately establish yield penalties or benefits from reducing cultivations, split field trials with adequate replication and randomisation are essential. These trials must be replicated on a variety of soil types and across multiple years and be supported by accurate yield and soil data. When accurate multiyear data is available, confidence from growers considering the change is likely to increase. It is important to acknowledge however that **crop quality is not a parameter routinely measured** with much research to data focussing on impacts to disease or environmental service provision typically.

A further challenge to uptake is the capital expense required to change machinery. In practice, a change from a plough and power harrow drill system to a minimal tillage system may offer cost savings over time on an area basis, however, the initial capital expense can be prohibitive. **In England**, this shift has been **addressed through grant aid (FETF Grant)**, where farmers have been able to access support to move towards reduced tillage systems, however, **no such support is available in Scotland at present**.

The rotational challenges (discussed below) can provide opportunities and challenges when considering a nationwide shift in tillage regime. A crop rotation can be used to mitigate against yield loss, allowing the maximum time before spring crops are established in a new system. For example, winter barley, followed by winter oilseed rape, followed by winter wheat could all be established by reduced tillage, before a spring barley crop is established in the fourth year of the system. This approach utilises crops which are at least risk of reduced cultivation to provide multiple years of soil restructuring to occur. Conversely, **rotational crops such as potatoes or vegetables can reverse many years of soil improvements from reduced tillage within a single season**, although recent research has found that the soil is more robust and can recover more quickly in this system.

Key research needs:

- Cultivar lists screened for performance based on tillage system
- Weed management strategies under reduced tillage
- Better understanding of temporal variability in yield or quality during the transition period
- Understanding the impact on gross margin during the transition phase and appropriate support
- Cost v benefit analysis of reducing tillage
- Understanding the drivers of impact from changing tillage practice, do some soils (e.g. sandy soils) respond better to changing practice. Is change in tillage practice dependent on underlying soil properties such as texture

2. Keep the soil-surface covered

Expert opinion

Covering the soil with living or dead plant material acts as a barrier to prevent erosion. **There are two main strategies to create permanent ground cover in Scotland: rotation and cover cropping**.

Rotation

Cropping in Scotland is split into autumn establishment and spring establishment where the soil is left bare over the winter months. The differentiation between autumn and spring establishment is essential to understanding the level of ground cover in Scotland throughout the year. Although autumn establishment offers a living cover, weak poorly established winter crops may not provide enough protection to prevent erosion. Spring crops, however can also offer varying levels of soil cover as land is often ploughed in the winter months (November to March). Across Scotland, there was 591,160ha of crops in 2025 of which 201,301ha (34%) is winter cropped. (Scottish Government, 2025). This suggests that there is **66% of the arable land in Scotland left bare overwinter** (in either a cultivated state or as stubble fields), less any cover crop area grown which is not detailed in the agricultural census. The change of crop rotation could provide an opportunity to move away from the current spring establishment dominance, to ensure that soil is covered through the winter months by winter crops, negating the requirement for cover crops which are notoriously challenging to establish.

Cover crops

Cover crops are comprised of multiple species sown in single species or mixtures. Therefore the impact will depend on the specific species used within the cover crops sown. **Cover cropping presents several challenges in Scotland**. The **most significant is the opportunity to establish cover crops** in the short window of opportunity during the autumn months, after harvest but before the weather cools. Experience has shown that cover crops must be established in August to ensure their success, however, many cash crops are harvested in September, limiting the opportunity to establish cover crops. For cover crops to be successful, an opportunity for establishment in August must be created by utilising early harvested crops such as vining peas, winter rye, winter barley or winter oats. These cereal crops are harvested earlier than winter wheat or spring barley and therefore offer a window for growers to establish cover crops. However, these crops are not widely grown compared to spring barley, as the markets is usually localised (either for feed barley or whole crop rye for anaerobic digestion). Alternatively new more low temperature low light tolerant cover crops would need to be developed or means to establish cover crops within the standing crop prior to harvest.

Table 4. Challenges and opportunities for keeping the soil-surface covered

Challenges to keeping the soil covered	**Opportunities from keeping the soil covered**

Workload constraints arising from delayed winter ploughing (stemming from limited labour availability and seasonally condensed workload).	A higher proportion of winter barley cropping makes harvest earlier.
Variability in cover crop establishment in Scotland, leading to reluctance for growers to invest.	Opportunity to introduce livestock to graze winter crops / cover crops. Links with principle 5.
Cost of establishing cover crops (seed and establishment costs) for no/limited financial return.	Potential to improve integrity of pore channels in soil to improve drainage leading to resilience in a wet spring.
Limited market demand for more winter crops. For example, winter barley market dominated by low value feed, with small premiums associated with winter malting barley.	Ability to 'prime' the soil system to promote nutrient cycling and gaseous exchange.
Increase in pests including challenges from slugs and wire worm.	

Scientific literature (Table 4)

Studies on cover crops and grain quality typically include catch crops and green manures (i.e., soil-improving non-cash crops) also. While these definitions for non-cash crops focus on defined functions and desired outcomes in the farming systems, there are clear overlaps with multiple ecosystem functions being delivered at the same time. For instance, a cover crop can protect the soil surface between main crops (e.g., during winter) and at the same time "catch" leftover soil nutrients. In general, cover crops, catch crops and green manures preserve soil structure and maintain the nutrient balance whilst contributing to the regenerative principle of "Keep the soil-surface covered" and "Keep living roots in the soil". For instance, a study by Olesen et al. (2009) investigated the effects of animal manure, green manures and catch crops on grain N and proteins in wheat. While grain N concentration increased with increasing N supply from the grass–clover green manure, **catch crops did not significantly affect cereal grain yield and reduced grain N concentration**, where no manure was applied. When compared to animal manure, N from green manure seemed to provide a greater effect on cereal grain N concentration due to its slow mineralisation.

When grain quality is the target, catch crops and green manures have received more attention compared to cover crops as it can be hypothesised that they **may have a greater effect on soil nutrient-status** and potentially plant health as they aim to improve plant nutrient-status**.** In the selected literature, catch crops and green manures were often tested as an alternative to conventional practices (e.g., Brandt 1996) or in combination with different practices (e.g., Çiçek et al. 2014; Olesen et al. 2009). When tested as alternative to conventional practices, **the degree of change and its significance often depended on the reference context and targets in input reductions**. The limited number of studies investigating the relation between "soil-improving non-cash crops" and grain quality, and the wider variety of "non-cash crops" treatments, do **not allow to derive robust conclusions**. However, it is interesting to note that some key processes and drivers have been identified in the

literature, such as the timing of residue mineralisation during the development of cereal crops. For instance, the slow mineralisation of plant material (e.g. green manures) can translate in N availability during the grain filling, leading to higher grain N.

Challenges and opportunities

The opportunity to adapt rotations to improve soil cover is largely limited by market demand. At present there is limited demand for winter barley, which would make a significant difference to the level of ground cover if replacing spring barley, both in the year it is grown and in the following year by providing an entry opportunity to sow cover crops. The potential to include other crops within the rotation is discussed below in the crop diversity section.

Cover crops provide limited opportunity within Scotland unless they are incentivised (no financial return at present for farmers). Monetising ecosystems benefit (i.e. reduced nitrate leaching, clean water, water eutrophication and flood mitigation) has not been undertaken in Scotland, with exception to the Tweed and Leven Landscape Enterprise Networks (LENs). **Cover crops will also need to be accompanied by an adaptation in the cropping rotation**. This adaptation is to ensure that they are established in good condition and consequently achieve complete ground cover. Further investigation is also required to understand the retention, release and timing of nitrogen availability by cover crops and their impact on subsequent crops of spring barley. **Understanding the nitrogen carry through is essential for planning fertiliser requirements** and ensuring malting barley grown after cover crops meets market specifications. **Some growers suggest that cover crops also negatively affect the workability of the soil in the spring**, by holding on to soil moisture and delaying spring crops from being established. Although, this is **contrary to what has been found in scientific literature**. These claims should be investigated further, to research the impact and legacy effect cover crops have on the water holding capacity of the soil throughout the winter of growth and the subsequent season.

Key research needs:

- Better understanding of nutrient availability, and release during the growing season, in subsequent cash crops following differing desiccation or destruction technique
- Impact of different cover crop mixes on nutrient status and release
- Nutrient release and grain quality through cover crop destruction techniques (roller crimping, glyphosate or grazing)

3. Keep living roots in the soil

Wheat and barley produced for the Scottish distilling market are annual crops, which presents a challenge when aiming to maintain a living root year-round. Although **changing the rotation to include more autumn cropping**, as mentioned above, presents opportunities for keeping the soil covered, it also highlights **opportunity to keep living roots in the soil**. Many of the practices used to implement living roots, have the added benefit of keeping the soil covered. In Scotland, the most common permanent ground cover is the use of temporary or permanent grassland. However,

the **inclusion of grassland within an arable rotation requires a significant systems change and the development of a local market for grass** – either from grazing livestock or anaerobic digestion. Although grassland offers a suitable crop to provide a living root, the likelihood of grassland gaining traction on arable farms is low due to the requirement to manage livestock. Furthermore, **intensively farmed grassland can introduce unintended consequences such as soil compaction from heavy silage making machinery, and the removal of high quantities of soil potassium reserves**. Winter barley provides a significant opportunity to improve soil cover across two winters (the year the crop is grown and the ability to establish a cover crop in the following year), alongside being more suitable to reduced cultivation techniques. However, **for winter barley to be widely grown, a change in market demand will need to occur**. Although it is acknowledged that there are challenges addressing dormancy break for maltsters.

4. Grow a diverse range of crops

Expert opinion

Crop diversity depends on the region and farming system within Scotland, with areas of Fife, Perthshire, Angus and the Lothians capable of producing a wide range of crops. However, in more marginal ground, the spectrum of crops capable of being grown is limited which results in the over reliance on a small number of crop species in these areas, particularly spring barley and grass. The suitability of land for producing a range of crops can be found on the Land Capability for Agriculture (LCA) webpage as part of the Scotland's soils website. This online tool details the capacity of land in Scotland to produce a diverse range of crops. The maps show that there is a minority area of Scotland which can produce a wide range of crops (LCA 1 and 2). **Most of the Scottish arable land falls within the classification 3.2, which is capable of average production**, although higher yields of barley, oats and grass are attainable. Although many Scottish producers grow legumes, potatoes, brassicas and cereals, cereal crops dominate the Scottish rotation. Classifying the level of diversity on Scottish farms depends on the parameters used. For example, a farm may produce wheat, barley and oats, however, as all species are annual grasses, this cropping mix is of limited belowground diversity. Additionally, a **diverse crop rotation may include potatoes, brassicas and carrots, but these crops are extremely intensive and are known to be detrimental to soil health**. In Tayside, spring barley accounted for ~36% of the total cropped area, whereas in the Grampian region spring barley accounted for ~59% of the crop area in 2025 (Scottish Government, 2025). The census data indicates that **crop diversity varies by region**, and therefore the opportunity to increase crop diversity may be regionally dependent and certainly LCA dependent. Furthermore, the census data is collected on a holding basis, and for true diversity, the range of crops must vary within field. For example, a mixed farmer may have 50% of the farm in grassland and 50% in spring barley, indicating a modest level of diversity. However, in practice the spring barley may be grown in the same fields every year indicating a monoculture.

Inter-cropping / bi-cropping are two farming techniques which at present are not common in Scotland (with exception to grass and clover sward mixes), however,

elsewhere in the world they are used to provide living root year-round. Research at James Hutton Institute has shown **benefits of mixing peas and spring barley, such as the structural stability of the bi-crop and the complementary root systems**. However, in practice, one on the most significant **challenges to bi-cropping is the control of weeds due to the lack of selective herbicides which are safe to use on both crops (peas and spring barley)**. This lack of suitable weed control options is likely to discourage many growers from adopting this practise. It can also increase the level of admixture (weed seeds) within grain samples, leading to reduced grain quality. Furthermore, inter-crops require specialist separation post-harvest to segregate the mixed crop into component parts to allow the produce to be marketed, if they are not being retained on farm.

Table 5. Challenges and opportunities for growing a diverse range of crops

Challenges to growing a diverse range of crops	**Opportunities to growing a diverse range of crops**
Market demand limited (spring barley preferred over winter barley)	Diversify income streams on farm
Some crops (potatoes and vegetables) improve diversity but are intensive and can cause soil damage	Spread workload on farm – variation in sowing and harvesting dates
Not all land can grow a wide range of crops	
Infrastructure on farm is not always suitable for multiple crops (one grain shed used for storing barley only)	

Scientific literature (Tables 5 and 8)

Scientific literature has recognised that **enhancing diversity** within agroecosystems, from genotypes to cropping systems, **can positively contribute to economic and ecological farming-sustainability**. For instance, Cope and Newton (2025) suggested that yield stability in barley can be achieved with increased genetic diversity. Similarly, Yan et al. (2025) found that **diversified cropping-systems increase wheat yield, yield stability and sustainability**. Grain quality has also been assessed in mixtures and intercropping systems. For example, Hummel et al. (2009) investigated the effects of wheat-canola intercrop on grain quality. Interestingly, the protein content of wheat-grain increased significantly following the increase in the proportion of canola in the intercrop. Moreover, **crop mixture can have positive indirect effects on grain quality by influencing the severity of pests and diseases**. Newton et al. (2002) reported a reduction in barley mildew in mixtures.

Until now, the **scientific literature does not present or suggest potential trade-offs between crop diversification and grain quality** however, these may appear in very specific circumstances. For instance, wheat following maize in the rotation has been found to have mycotoxins concentrations six times higher than under continuous wheat (Champeil et al. 2004). Moreover, this negative effect can be very specific to the management practice and grain use. For example, mycotoxins contamination in

wheat grain is higher following grain-maize in respect to wheat following forage-maize. It was suggested that the reason for this was that more crop debris results from the harvesting of grain-maize compared to forage-maize (Edwards 2004). Arable weeds and companion plants should also be considered when mycotoxins contamination is a concern for grain quality. A large weed population increases the number of species of Fusarium causing head blight and mycotoxin contamination in wheat. Grass weeds have been suspected to act as a source of inoculum whereas other weeds have been thought to favour infection by modifying the microclimate surrounding the crop (Champeil et al. 2004). Therefore, **while the environmental and yield-stability benefices of crop-diversification are well recognised, more work is needed in the case of grain quality**. In particular, mechanisms and potential trade-offs may vary largely in relation to the level of diversification (genetic – species in mixtures – rotations) as well as the functional traits brought together with crop diversification.

Challenges and opportunities

Overall, diversity of crop production must be at the landscape, farm and field scale, with each tier providing separate benefits to the end user, farming business and soil health. On some holdings there is large potential to increase diversity, however, some businesses are already highly diversified and provide little opportunity. The variation of crop diversity can be characterised by farming region; however, this is not exclusive and all farming regions have a range in diversity. It is recommended that 'crop diversity' is defined, whether that be to the plant family, species or cultivar level, so that the opportunity to increase diversity can be calculated.

Key research needs:

- Define what 'diversity' means within the agronomic landscape, be that diversity of root functional, species, or cultivar

5. Bringing grazing animals back to the land

Expert opinion

Grazing livestock depends largely on the integration of livestock and crop enterprises within a farming business (mixed farming) or the proximity of livestock and cropping businesses willing to collaborate. In both instances, this integration is primarily driven by the land capability on farm, with farming units with areas of poorer land more likely to have livestock. In recent years, there has been an **increase in interest from arable farmers who would like to integrate livestock by grazing cover crops or grazing winter cereals**. Although these examples are limited, they offer a potential opportunity to integrate two farming systems.

One of the most common ways to integrate components of livestock into arable systems is the use of farmyard manures (straw for dung agreements). Although this is not a direct introduction of grazing animals, the availability of **manures provides an organic amendment which can have significant influences (positive and negative) on soil health and grain yield and quality**. Farmers who routinely apply organic

manures have reported a perception that soil has an increased resilience to drought which leads to more consistent grain yield and quality. The integration of manure relies on strong working relationships and trust between the arable and livestock farmers, and the proximity of the farming units. Due to the bulky nature of farmyard manures, haulage is costly and therefore the livestock and arable farms must be close together to make this solution economically viable.

Table 6. Challenges and opportunities for grazing and integrating livestock

Challenges to grazing livestock / livestock integration	**Opportunities to grazing livestock / livestock integration**
Limited knowledge of livestock husbandry by arable farmers.	Improved water holding capacity.
Lack of infrastructure (fences/ sheds).	Management of forward / well developed cereal crops.
Availability of consistent feed sources (cover crops are seasonal).	Diverse income streams.
Management / time requirement for stock husbandry.	

Scientific literature (Tables 6 and 7)

The systematic review of scientific literature identified only one study on the effect of livestock integration (i.e., grazing of oat) on barley in an arable system (Hu et al. 2020). This study assessed the effect of soil compaction and urea input during grazing, and a potential mitigation strategy (no-till). Urea inputs during grazing promoted vegetative growth of barley but restricted its reproductive growth (i.e. grain yield). Urea input showed negative effects on seed weight, harvest index, ear population, screenings, and hectolitre weight. **Barley following a grazing-crop (oat) established using no-till practice, had lower screenings than barley following a grazing-crop established in a plough system**. This translated in a more marketable grain. It should be noted that there is **limited scientific evidence on the positive effects associated with "bring grazing animals back to the land"**. Moreover, the British Ecological Society report on Regenerative Agriculture in the UK has clearly warned on the negative impacts associated with mix-farming promotion as **an increase in livestock numbers will have knock-on effects in terms of total emissions and other environmental externalities**.

Seven studies have investigated the effect of animal manure on grain quality. These studies were published between 2003 and 2025 and included manure from different livestock systems. For instance, a study by Wen et al. (2003) assessed the effects of both liquid pig manure and cattle manure on wheat. Interestingly, despite the fact that the wheat crop utilised residual pig and cattle manure N equally in producing grain yield, a **higher grain N concentration with the cattle compared to the pig manure revealed different N supply dynamics between the manures**. This could possibly be related to the slow mineralization of cattle manure, which provided more available N in the later stage of wheat growth than did the pig manure. In other studies, animal manure is compared with green manure (e.g., Olesen et al. 2009). **Grain N concentration increased with increasing N supply from the grass–clover pre-**

crop. N from grass–clover seemed to provide a better effect on cereal grain N concentration than the animal manure application. This was probably caused by the different timing of N availability in green and animal manure. The slower mineralisation of the organic matter in the grass–clover probably increased late season N uptake, affecting grain protein content.

Challenges and opportunities

Although livestock integration could provide significant improvement to arable farms, the economics associated with grass leys or straw for dung agreements are often prohibitive. Furthermore, the potential to increase reliance on farmyard manures is limited by the availability of manure, which is driven by a declining national cattle herd and sheep flock. This suggests that should the trend of declining livestock numbers continue, the availability of grazing livestock and the associated manure will reduce over time. In a situation where no livestock manure is available, the chopping and incorporation of cereal straw can bring benefits to the soil functionality.

Key research needs:

- Understand availability and opportunities to incorporate livestock more widely into farming system. For example, links with other livestock farmers who may provide sheep to graze winter cereals
- The role of livestock in grazing winter cereals and impact on grain quality driven by potential nutrient availability

Peer-reviewed scientific literature

Table 3: Reduced tillage

Authors	Year	Title	Crop	Regen practices	Grain-quality	Outcome
Bullied, W.J.; Entz, M.H.	1999	Soil water dynamics after alfalfa as influenced by crop termination technique	Alfalfa and Spring Wheat	Tillage with and without herbicide termination	Grain yield	**The best overall system was Herbicide (no-till) termination after the second hay harvest**. This approach: 1) Conserved and recharged more soil water. 2) Maintained high residue cover. 3) Produced the highest wheat yields and WUE. 4) Outperformed the traditional practice of early, intensive tillage after the first hay cut.
Carter, M.R.; Gupta, U.C.	1997	Micronutrient concentrations in barley and soybean under minimum tillage on podzolic soils in a cool climate	Spring Barley , Soybean	The study compared conventional and reduced tillage systems: Mouldboard ploughing (spring or fall) Para plough + direct drilling Chisel ploughing (spring or fall) Rotary harrow Disc harrow Direct drilling (5 cm depth)	Micronutrients in grain, Yield	Crop yields: Generally similar among tillage treatments. Micronutrient trends: **Cu and Zn were most affected by tillage, slightly lower under direct drilling compared to mouldboard ploughing.** **Mn and Fe decreased under shallow tillage and direct drilling in some cases**. Mo showed a decline over time under all tillage systems, especially in barley grain. Soybean grain had much higher B and Mo concentrations than barley. Despite variations, micronutrient concentrations remained within sufficiency ranges for crop growth and feed quality.

Gao, X.; Grant, C.A.	2012	Cadmium and zinc concentration in grain of durum wheat in relation to phosphorus fertilisation, crop sequence and tillage management	Durum wheat in Canada, multi-year study (1999-2003)	Tillage (conventional and reduced) and P treatments	Yield, cadmium and zinc	Grain yield increased under reduced tillage in 3 sites (better under conventional tillage at 1 site in 1 year), limited fertiliser effect. **Grain Cd was typically reduced under reduced tillage. Zn increased in grain in 2 years under reduced tillage, one site however showed no influence of tillage on Zn accumulation.** Note. pH range: 7.5 – 8.4
Gao, X.; Grant, C.A.	2011	Interactive effect of N fertilisation and tillage management on Zn biofortification in durum wheat (Triticum durum)	Durum wheat	Two Tillage (reduced tillage (RT) and conventional tillage (CT) - Tillage operations were not conducted on the RT plots, but the stubble was mowed with a rotary mower to simulate the effects of a straw chopper) Four N sources - Nitrogen fertiliser treatments consisted of a control without extra N application and application of 60 kg N ha1 in addition to the background N using four N sources, i.e., anhydrous ammonia (NH3 82-0-0), urea ammonium nitrate (UAN 28-0-0), urea (46-0-0), and ammonium nitrate (AN 34-0-0)	Yield, grain Zn concentration	Soil type also had a dominating effect, with grain Zn concentration generally being higher at the clay loam location than the fine sandy loam location. **Tillage management showed little influence on grain Zn, suggesting that reduced tillage practices can be adopted by local farmers without decreasing mineral concentrations in grain**

Izaurralde, R.C.; Juma, N.G.; McGill, W.B.; Chanasyk, D.S.; Pawluk, S.; Dudas, M.J.	1993	Performance of conventional and alternative cropping systems in cryoboreal subhumid central Alberta	Barley	Tillage		Inconclusive but **no penalty in no till under** 2 soil types
Malhi, S.S.; Lemke, R.L.	2007	Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emissions in a second 4-yr rotation cycle	Barley (*Hordeum vulgare*) wheat (*Triticum aestivum*), Canola (*Brassica napus*)	Tillage (no-tillage – NT and conventional tillage – CT), straw management (straw retained – R and straw not retained – NR) and N fertilizer (0, 40, 80 and 120 kg N/ha)	Grain yield, N and C content in grain	**Tillage had significant effect on grain, straw and chaff yield for barley** (in 2002), as well as on grain yield and root mass for wheat (in 2004). Seed, straw and chaff yield of barley in 2002 were significantly greater with NT compared with CT by 51%, 23%, and 13%, respectively. **Straw retention increased seed, straw, chaff and root yield compared to straw removal for barley** in 2002, pea in 2003 and wheat in 2004. Seed, straw and chaff yield, and root mass of barley in 2002 were greater with R compared with NR by 62%, 43%,12% and 11%, respectively. The barley seed yield and root mass in 2002 were greatest with NT + R, but in 2004 wheat seed yield was greatest with CT + R. The beneficial effect of straw retention on barley yield thus appeared to be relatively greater under NT than CT. **The beneficial effect of NT and straw return on crop yield is accomplished mainly through conservation of soil moisture in dry periods, and improvement in soil properties** (which is a slow process). The greater yield of barley under NT compared to CT (particularly where straw was returned) in 2002, was explained with below-average precipitations during the

						year. **Mass of N and C in barley was greater under NT than CT, and also greater with R than NR**.
Malhi, S.S.; Lemke, R.L.; Wang, Z.H.; Chhabra, B.S.	2006	Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions	Wheat and barley	No till and straw incorporation	Seed, straw and chaff yield	**Returning crop residue and no tillage had no significant effect on barley yield but a sig effect on wheat straw and chaff yield**
McConkey, B.; Campbell, C.A.; Zentner, R.P.; Dyck, F.B.; Selles, F.	1996	Long-term tillage effects on spring wheat production on three soil textures in the brown soil zone	spring wheat (*Triticum aestivum*) (on the silt loam and clay), durum (*Triticum turgidum*) (on the sandy loam)	No-tillage (NT), minimum tillage (MT), conventional tillage (CT)	Grain yield, grain N	**On the sandy soil with its low water-holding characteristics, tillage system did not affect stored spring soil moisture**, nor grain yields, nor grain N. On the silt loam and clay, there were several instances when NT increased stored moisture in the soil, especially on the clay, but the extra moisture conserved was not always associated with increased grain yields.
McConkey, B.; Curtin, D.; Campbell, C.A.; Brandt, S.; Selles, F.	2002	Crop and soil nitrogen status of tilled and no-tillage systems in semiarid regions of Saskatchewan	Wheat (*Triticum aestivum* and *Triticum durum*)	Tilled and no-till systems (1990-1996) and on 3 sites in Canada and a mix of continuous wheat or fallow-wheat rotation. First 8-12 years following conversion from inversion tillage not studied	Yield, protein, crop N and microbial biomass	Site 1 showed that wheat yield slightly higher ~7% (not ns) following fallow in NT (no tillage) vs MT (minimum tillage) treatments. Continuous wheat yield was higher for NT 11% with no tillage effects on grain protein. Site 2 showed that fallow-wheat yield was 9% greater in CT v NT and 5% greater in MT v NT however variability between years. Protein content was 8% and 6% lower under CT and MT respectively however, again, variability between years. Hypotheses that N availability was lower in NT compared to till systems. In continuous wheat there were no tillage effects on yield or protein concentration. At site 3, grain protein on fallow-wheat and continuous wheat was 7%

						less in NT compared to MT ut not significant. Typically, grain yield lower under NT compared to MT but only significantly in 1 year (1996). **Indications that conversion to NT and MT results in lower N availability and therefore lower grain protein in wheat**. This is based on the idea the yields were unaffected by tillage however protein was lower and therefore diluted by N availability. Important to note that this is the impact on quality 8-12 years after conversion to different tillage system. May be a need to increase N application to compensate.
O'Donovan, J.T.; Turkington, T.K.; Edney, M.J.; Juskiw, P.E.; McKenzie, R.H.; Harker, K.N.; Clayton, G.W.; Lafond, G.P.; Grant, C.A.; Brandt, S.; Johnson, E.N.; May, W.E.; Smith, E.G.	2012	Effect of seeding date and seeding rate on malting barley production in western Canada	Malting barley	No tillage production	Yield, grain protein, seed plumpness	Influence of sowing date and rate under no till on yield and malting barley quality. **Typically, planting later increased grain protein content associated with higher temperatures later in the growing season** however the increase was dependent on site. Rejection due to high protein is a potential issue with late sowing. **Delayed seeding may also decrease plumpness and reduce likelihood of achieving malting grade**. **Protein content decreased with increased sowing rate. Increased sowing rate also increased grain size uniformity**.

Riley, H.C.F.	1998	Soil mineral-N and N-fertilizer requirements of spring cereals in two long-term tillage trials on loam soil in southeast Norway	Spring Barley and Spring Wheat	Reduced Tillage and Conservation Tillage, N Fertiliser treatments	Grain Yield, Grain and Straw N concentration, Total N uptake	**Long-term reduced tillage does not alter nitrogen fertiliser requirements, soil N mineralisation, or final yields of spring cereals on loam soils under cool climatic conditions**. While reduced tillage changed some soil physical properties and slightly altered early crop development, these effects did not translate into consistent differences in soil N supply, fertiliser response, or yield performance compared with conventional ploughing.
Soon, Y.K.; Clayton, G.W.	2002	Eight years of crop rotation and tillage effects on crop production and N fertilizer use	Wheat	No till and rotations	Yield and N, P and K in grain	No tillage or rotation effects grain nutrient content. **During second rotation wheat yield increased 22% in NT but NT reduced yield in first rotation. Wheat yield increasing after red clover and field pea.**

Table 4: Cover crops and green manure

Authors	Year	Title	Crop	Regen practices	Grain-quality	Outcome
Brandt, S.	1999	Management practices for black lentil green manure for the semi-arid Canadian prairies	Wheat, lentil (green manure)	Green manure (black lentil), with summer fallow control, management practices for herbicide and soil incorporation.	Yield and protein	Green manure impacts on water infiltration following snow. **No significant effects of management on grain protein** (14.6-14.9%) or yield.
Brandt, S.	1996	Alternatives to summer fallow and subsequent wheat and barley yield on a Dark Brown soil	Green-manure and grain lentil (*Lens culinaris*) field pea (*Prsu m sativum*), wheat (*Triticum aestivum*), barley (Hordeum vulgare)	Green manure as alternative to summer fallow	Grain yield	**Yield of wheat grown after lentil green manure was similar to yield of wheat on summer-fallow.** Yield of barley grown the following year was generally unaffected by summer-fallow or summer-fallow substitute treatments.
Brozyna, M.A.; Petersen, S.O.; Chirinda, N.; Olesen, J.E.	2013	Effects of grass-clover management and cover crops on nitrogen cycling and nitrous oxide emissions in a stockless organic crop rotation	Wheat and barley within a 4-year organic cropping system	Cover crop and under-sown clover. Green manure incorporation and removal of biomass (for assumed use as digestate feed material) (-M) and replacement with pig manure co-digested with 20% organic residues (+M)	Yield, N content of grains and grain dry matter content	Dry matter yield increased significantly for winter wheat but not spring barley when fertilised with manure application rather than just residues **Reduced N loss through removal of biomass for digestate for re-application**.

Çiçek, H.; Thiessen Martens, J.R.T.; Bamford, K.C.; Entz, M.H.	2014	Forage potential of six leguminous green manures and effect of grazing on following grain crops	Pea/Oat mix (Pisum sativum cv. 40–10 / *Avena sativa* cv. Legget) – used as the standard. Hairy vetch (*Vicia villosa*). Sweet clover (*Melilotus officinalis* cv. Norgold). Lentil (*Lens culinaris* cv. Indianhead). Soybean (Glycine max cv. Prudence). Mixture (seven species: barley, field pea, millet, radish, soybean, turnip, sunflower).	Grazing: Green manures grazed by 2–3 ewes and 2–5 lambs for 24 hours (1111–1667 sheep days per ha). Incorporation: Green manures terminated and disked into soil without grazing.	Biomass (DM). Grain yield. Nitrogen (N) uptake (kg/ha). Grain N concentration.	Utilisation of green manures by grazing animals varied little among species across years and ranged from 28 to 86% for individual species and years. When combined across experiments **grazing increased N availability to the wheat crop**. The grazing effect was significant for wheat DM production, N uptake and grain N, but not significant for yield across experiments. A significant species × management interaction for total (wheat +fall rye) N uptake in 2009 indicated that **increasing the proportion of legumes in the green manure increased N benefit from grazing** Grazing legumes did not provide more N benefit than pea/oat; only hairy vetch and pea/oat met the benchmark for N supply (>110 kg N/ha).
Olesen, J.E.; Askegaard, M.; Rasmussen, I.A.	2009	Winter cereal yields as affected by animal manure and green manure in organic arable farming	Crop rotation was spring barley under sown with grass/clover – grass/clover – winter wheat or wheat rye – pulse crop	Animal manure, green manures, catch crops	Grain yield, grain N, grain protein	**Grain N concentration increased with increasing N supply from the grass–clover pre-crop**. **Catch crops in systems did not significantly affect cereal grain yield, but reduced grain N concentration**, in particular where no manure was applied. N from grass–clover seems to provide a better effect on cereal grain N concentration than the manure application. This is probably caused by the different timing of the

						availability of N in the various N sources. A relatively high proportion of the applied N in manure was in the form of mineral N (52–75%), and this N primarily contributed to increasing leaf area index and grain yield. **The slower mineralisation of the organic matter in the incorporated grass–clover probably increased late season N uptake thereby primarily affecting grain protein content**.

Table 5: Crop and rotation diversification

Authors	Year	Title	Crop	Regen practices	Grain-quality	Outcome
Cope, J.E.; Newton, A.C.	2025	Performance of elite and heritage germplasm in barley genotype mixtures: effects on yield and disease under diverse management scenarios	Spring and Winter Barley including heritage lines	Increased diversity (Barley genetic diversity - Mixtures)	Yield stability	**Yield stability could be achieved with increased genetic diversity** of the correct type and appropriate environmental conditions (including management) although yields rarely achieved those of elite monoculture.
Hummel, J.D.; Dosdall, L.M.; Clayton, G.W.; Turkington, T.K.; Lupwayi, N.Z.; Neil Harker, K.; O'Donovan, J.T.	2009	Canola-wheat intercrops for improved agronomic performance and integrated pest management	Intercrops of canola (*Brassica napus*) and wheat (*Triticum aestivum*)	Intercropping	aboveground biomass, 1000-kernel weight (TKW), N content, percent protein	**Crop grain yields for intercrops were not different compared to monocultures**. Wheat TKW was significantly cantily affected by the proportion of canola comprising the intercrop, such that as the proportion of canola increased, TKW for wheat decreased. **Protein content of wheat increased significantly with increases in the proportion of canola**
Kröbel, R.; Campbell, C.A.; Zentner, R.P.; Lemke, R.L.; Desjardins, R.L.; Karimi-Zindashty, Y	2012	Effect of N, P and cropping frequency on nitrogen use efficiencies of spring wheat in the Canadian semi-arid prairie	Spring Wheat	Continuous Wheat vs Fallow-Wheat rotations	Grain yield (Y) (kg ha^{-1}), Grain nitrogen content (GN) (kg N ha^{-1})	Average efficiencies (1967–2005): Balance method (including all N sources): ~11 kg grain per kg available N ~0.28 kg grain N per kg available N for continuous wheat ~0.32 kg grain N per kg available N for fallow–wheat–wheat Difference method: Much smaller values (e.g., 0.11 vs. 0.04 kg grain N per kg available N for continuous vs. fallow systems)

						Continuous wheat had lower NUE than fallow-based rotations when calculated by the balance method, but the reverse was true with the difference method.
Newton, A.C.; Guy, D.C.; Nadziak, J.; Gacek, E.S.	2002	The effect of inoculum pressure, germplasm selection and environment on spring barley cultivar mixtures efficacy	Spring barley	Mixtures	Yield, heading date, lodging	**Mildew reduced in mixtures** and reduced lodging influencing heading date also and improving yield but results were variable over the years of the study. Benefits associated with **increased disease resistance in mixtures**
Yan, Z.; Xu, Y.; Chu, J.; Guillaume, T.; Bragazza, L.; Li, H.; Shen, Y.; Yang, Y.; Zeng, Z.; Zang, H.	2025	Long-term diversified cropping promotes wheat yield and sustainability across contrasting climates: Evidence from China and Switzerland	Winter Wheat in rotations with (Switzerland, sub-maritime climate) OSR and Maize and (China continental climate) Peanut and Maize.	Switzerland Diversified rotation Wheat-OSR-Wheat-Maize and two tillage treatments (Shallow and deep plough); China Peanut-wheat-maize. Regenerative principles 1) Increased crop diversity, fixing nitrogen (peanuts), reduced chemical inputs.	Yield, Yield stability	**Diversified cropping increased wheat yield, yield stability and sustainability**. Wheat yield Increased Switzerland: +16.2; China: +15.0% Wheat Yield Stability & Sustainability Improved Switzerland: Stability: +5–6%; Sustainability: +13–22% China: Stability: +3.7%Sustainability: +12.3%

Table 6: Mixed farming

Authors	Year	Title	Crop	Regen practices	Grain-quality	Outcome
Hu, W.; Beare, M.; Tregurtha, C.; Gillespie, R.; Lehto, K.; Tregurtha, R.; Gosden, P.; Glasson, S.; Dellow, S.; George, M.; Tabley, F.; Qiu, W.; Baird, D.	**2020**	Effects of tillage, compaction and nitrogen inputs on crop production and nitrogen losses following simulated forage crop grazing	Barley, oat as grazing/preceding crop	Livestock winter grazing of forage crops on cultivated soils. The study investigates how compaction and high inputs of N from livestock urine (urea) during winter grazing affect subsequent barley production and whether establishing winter-grazed forage crops with no-tillage can mitigate potential adverse effects on subsequent crop.	Grain yield, N contents, seed weight, harvest index, ear population, screenings, and hectolitre weight of seed	**Barley following a grazing-crop (oat) established using no-till practice has lower screenings than barley following a grazing-crop established in a plough system. This translates in more marketable grain**. Urea inputs during grazing promotes vegetative growth of barley but restrict its reproductive growth (i.e. grain yield). **Urea input has also negative effects on seed weight, harvest index, ear population, screenings, and hectolitre weight**

Take 7: Reduced synthetic inputs and use of organic inputs

Authors	Year	Title	Crop	Regen practices	Grain-quality	Outcome
Bernhoft, A.; Clasen, P.-E.; Kristoffersen, A.B.; Torp, M.	2010	Less Fusarium infestation and mycotoxin contamination in organic than in conventional cereals	Barley, Oats, Wheat	Organic vs Conventional	Mycotoxin content	**Organic cereals had significantly lower Fusarium infestation and mycotoxin levels than conventional cereals across all species.** Key findings by crop and toxin: Oats: HT-2 median: <20 µg/kg (organic) vs. 62 µg/kg (conventional). Mycotoxin median: 24 µg/kg (organic) vs. 36 µg/kg (conventional). Wheat: **Mycotoxin median: 29 µg/kg (organic) vs. 51 µg/kg (conventional).** Barley: Lower HT-2 and T-2 in organic samples.
Iqbal, M.; Semagn, K.; Cerón-Rojas, J.J.; Crossa, J.; Jarquín, D.; Howard, R.; Beres, B.L.; Strenzke, K.; Ciechanowska, I.; Spaner, D.	2022	Identification of Spring Wheat with Superior Agronomic Performance under Contrasting Nitrogen Managements Using Linear Phenotypic Selection Indices	Spring Wheat	Conventional (Barley-OSR=Field Pea-Wheat) vs Organic (Barley-Field Pea-Wheat)	Yield, grain protein concentration (GPC)	Yield: 4.0–6.2 t/ha (higher in organic vs conventional Grain yield and GPC were negatively correlated (r ≈ –0.56). **Grain protein concentration: 14.6–17.7% (less in organic vs conventional)**

Mooleki, S.P.; Schoenau, J.; Charles, J.L.; Wen, G.	2004	Effect of rate, frequency and incorporation of feedlot cattle manure on soil nitrogen availability, crop performance and nitrogen use efficiency in east-central Saskatchewan	Canola (*Brassica napus*), spring wheat (*Triticum aestivum*), hull less barley (*Hordeum vulgare*)	Application of feedlot cattle manure at different application rates, frequencies and incorporation timing in a sandy loam and loam soil. Three rates of feedlot cattle manure (approx. 100, 200 and 400 kg total N ha) were applied annually and under reduced frequency application regimes.	Grain yield, grain N	**Annual application of cattle manure resulted in a linear increase in grain yield with application rates**. However, if no new cattle manure applications are made, significant residual effects of a one-time manure application may not last more than 2 years. **Cattle manure application had limited effect on grain N.**
Olesen, J.E.; Hansen, E.M.; Askegaard, M.; Rasmussen, I.A.	2007	The value of catch crops and organic manures for spring barley in organic arable farming	Spring barley	Slurry v catch crop	Dry matter and NUE	**Slurry increased dry matter yield greater than catch crop with spring barley.** NUE :1/3 lower in catch crops than through slurry application but study suggests caution in this finding.
Paire, L.; McCabe, C.; McCabe, T.	2025	Multi-year organic field evaluation of a diverse panel of spring naked barley accessions for feed, food, and malting use	Spring Barley (Naked)	Organic, No Fertiliser inputs, cattle manure, hand weeding	Yield, harvest index, TKW, Screenings (%>2.5mm), threshability, protein content, beta glucan content, Malting quality - germinative energy	No treatment effects tested, assessment of genotypic variation only Genotypic effects were significant with heritability >60% → strong potential for selection. Genotype × year interactions were significant, showing the importance of trait stability across variable climates. Fundamentally, the study **looks at grain quality from naked barley lines under a ploughed organic system**. Quality only addressed from breeding perspective, no commercial varieties used as control

Turkington, T.K.; O'Donovan, J.T.; Edney, M.J.; Juskiw, P.E.; McKenzie, R.H.; Harker, K.N.; Clayton, G.W.; Xi, K.; Lafond, G.P.; Irvine, R.B.; Brandt, S.; Johnson, E.N.; May, W.E.; Smith, E.G.	2012	Effect of crop residue, nitrogen rate and fungicide application on malting barley productivity, quality, and foliar disease severity	Malting barley quality under no till with different	No till production across 7 sites with N fertiliser rates of 50% or 100% with residues incorporated (barley, canola and field pea) and either fungicide or no fungicide applied 2006-2009)	Yield, protein, TGW, seed plumpness, disease	Largest source of variation being site-year, barley planted into barley residue resulted in 2.5 x total leaf disease severity compared to canola an field pea incorporation. Disease resulted in yield losses of ~20%. Barley planted following barley incorporation reduced emergence, head counts, yield and kernel plumpness. Yields highest following planting after field pea residue incorporation, potentially due to N. Canola impact potentially linked to being non mycorrhizal with potential in reduced mycorrhizal activity in following crops. **N application rate influenced yield and quality with a reduction associated with 50% reduction in N application** with no impact on disease. **Fungicide applications increased yield, TGW, plumpness**.
Wen, G.; Schoenau, J.; Charles, J.L.; Inanaga, S.	2003	Efficiency parameters of nitrogen in hog and cattle manure in the second year following application	Canola (Brassica napus), spring wheat (Triticum aestivum)	Liquid hog (pig) manure and cattle manure	Grain yield, grain N	Wheat yield was positively correlated with increased rate of manure N applied in the previous year. However, despite that the **wheat crop utilized residual hog and cattle manure N equally** efficient in producing grain yield, a **higher grain N concentration with the cattle than with the hog manure revealed different N supply dynamics between the manures**. Possibly due to the low proportion of ammonium (NH3)-N in the total N and the high C:N ratio in the cattle manure, mineralization of **cattle manure provided more available N in the later stage of wheat growth than did the hog manure**.

Table 8: Reviews including different agricultural practices – focus on mycotoxins

Authors	Year	Title	Crop	Regen practices	Grain-quality	Outcome
Edwards, S.G.	2004	Influence of agricultural practices on fusarium infection of cereals and subsequent contamination of grain by trichothecene mycotoxins	Wheat	Several agricultural practices are considered in this literature revie: crop rotation, soil cultivation, fertiliser application, weed control	Fusarium head blight and trichothecene mycotoxins contamination in grain	**Crop rotation**: conflicting evidence and differences between crops preceding wheat. For instance, wheat following maize has shown the highest contamination of mycotoxins, in particular grain maize was higher than forage maize. It was suggested that the reason for this was that more crop debris results from the harvesting of grain compared to forage maize. **Soil cultivation**: minimum tillage instead of ploughing after a maize crop could result in a 10-fold increase in mycotoxin contamination of the following wheat crop **Fertiliser application**: Increasing the amount of nitrogen applied to cereals can result in increased incidence of fusarium-infected grain. The form in which nitrogen is applied may also have an effect. For instance, wheat fertilised by urea had fewer symptoms of fusarium infection than wheat fertilised by ammonium nitrate. **Weed control**: High weed density has been shown to result in increased fusarium head blight. The use of glyphosate has also been correlated with increase of fusarium head blight in wheat.

Champeil, A.; Doré, T.; Fourbet, J.F.	2004	Fusarium head blight: Epidemiological origin of the effects of cultural practices on head blight attacks and the production of mycotoxins by Fusarium in wheat grains	Wheat	Several agricultural practices are considered in this literature revie including crop rotation, soil tillage, fertiliser application, weed control	Fusarium head blight and mycotoxins contaminatio n in grain	Cultural practices and head blight disease **Crop rotation**: The shorter the rotation, the higher the frequency of head blight. However, the density of crop residues left in the field, their nutritional value and pathogen competition may also modify the effect of crop rotation. Head blight contamination is more severe if the preceding crop is maize, durum wheat or oats, rather than wheat or barley. **Soil tillage**: Limited soil tillage increases the frequency of head blight, whereas deep tillage (ploughing) decreases it. **Fertiliser application**: Nitrogen application significantly increases the incidence of Fusarium infection in grains of wheat, barley and triticale. **Weeds**: Large weed population increases the number of species of Fusarium causing head blight in wheat, as does the intensity of the disease. Grass weeds have been suspected to act as a source of inoculum whereas other weeds have been thought to favour infection in a different way, by modifying the microclimate, increasing heat and humidity Cultural practices and mycotoxin production: **Soil tillage**: There is a significant positive correlation between intensity of soil tillage (ploughing and direct drill) and mycotoxin concentration in grains. **Crop rotation**: Wheat following maize in the rotation has been found to have deoxynivalenol concentrations six times higher than those in wheat following another cereal (wheat, barley) or soybean.

Grey literature

Table 9: Grey literature - Reports

Authors	Year	Title	Crop	Regen practices	Grain-quality	Outcome
Fiennes, J.	2025	Regenerative Agriculture in the UK: An ecological perspective	No focus on a single crop, however; cereals (wheat and barley) are referenced, as are grazing livestock (grassland). Indirect reference made to horticultural crops such as vegetables and fruit.	Minimising soil disturbance, keeping living roots year-round, increasing on-farm diversity, integrating livestock (or equivalent functions), and reducing synthetic inputs in favour of ecological approaches.	Grain yield and consistency. Protein content.	The BES 2025 report finds that regenerative agricultural practices can initially **reduce grain yields during the transition phase but often improve yield stability and grain quality over time**. Practices such as reduced tillage, cover cropping, and integrating livestock enhance soil health, biodiversity, and resilience, which in turn support more consistent yields and better grain quality. *Conclusions:* The transition phase (3-6 years) is critical as yields may dip but resilience and quality gains emerge in time. **Quality improvements are more consistent than yield gains, especially in protein content and reduced chemical residues in grain**.

Cooper, J., Stockdale, E. and Clarke, B.	2024	D2: A summary of key knowledge gaps, research needs and ways to address them	Cereals (wheat, barley and oats), legumes (peas, beans and clover as intercrops and cover crops). Limited evidence on root crops (sugar beet and potatoes).	Reduced tillage, cover cropping, intercropping, variety blends, and integration of legumes	Grain yield. Protein content. Malting barley grain nitrogen. Micronutrient content.	**The report finds that regenerative agriculture practices can influence grain yield and quality, but evidence is mixed and highly context dependent.** Practices such as reduced tillage, cover cropping, intercropping, variety blends, and integration of legumes show potential benefits for soil health and resilience, but their impacts on yield and grain quality vary by crop, environment, and management intensity. *Conclusions:* This report highlights that regenerative agriculture can support sustainable grain production, but consistent quality for premium markets (malting and milling) remains a challenge without tailored rotations and variety selection. It suggests that the evidence base is fragmented with few long-term studies that directly measure grain quality outcomes under regenerative systems. Furthermore, regenerative systems often prioritise soil health and resilience over short term yield. Finally, the report suggests that long-term trials on malting barley and bread wheat under regenerative rotations, especially focusing on nitrogen dynamics, disease resistance, and end-market quality are required.

Cunningham-Eurish, I., Wentworth, J.	2025	Regenerative Agriculture	The briefing paper does not focus on one crop but discusses regenerative practices across UK arable systems.	No/low tillage, cover crops and grass leys, crop residues, plant diversity, integration of livestock, and reduced chemical inputs.	Yield. Grain protein. Nutrient density. Grain N content of malting barley.	The POST note on Regenerative Agriculture concludes that regenerative practices can improve soil health, biodiversity, and resilience, but their **direct impacts on grain yield and quality are mixed and highly context dependent**. Short-term yield reductions may occur, especially when practices are applied singly, but combining multiple practices often stabilises or improves productivity. **Grain quality outcomes (protein and nutrient density) are influenced by nitrogen management, soil health, and crop diversity, with evidence suggesting both opportunities and trade-offs.** *Conclusions:* Regenerative Agriculture can cause short term yield reduction but stabilises under multiple integrated practises. Nitrogen management is a key consideration to ensure that grain protein and grain nitrogen specifications are met.

Jenkins, T., Randall, N.	2025	Research Review 101a Updating cover crop guidance (Part A): destruction methods	Cover Crops.	Cover crop (destruction methods).	Grain yield. Admixture (weed seeds).	5 cover crop termination methods were trialled (grazing, mechanical, chemical, frost-kill and combinations). **It was found that the termination method directly affects soil nitrogen dynamics, leading to variable protein content in cereals.** Poorly timed cover crop termination can also result in increased weed burden resulting in contaminated grain lots. *Conclusions:* **Cover crop destruction method and timing determine whether benefits to soil health translate into higher yields and better grain quality**. In the UK, chemical termination remains dominant; while grazing and mechanical methods offer potential but require careful management to avoid soil compaction and weed burdens. It was found that the management of the cover crop will influence the impact the cover crop has on both yield and quality of the subsequent crop.

Spink, J., Hennessy, M., Hackett, R., Wall., D.	2025	An environmental and economic assessment on the impact of possible reductions in the maximum chemical nitrogen allowances for main arable crops.	Winter wheat, winter barley, spring barley.	Reduced chemical inputs (nitrogen fertiliser).	Grain yield. Protein content.	Lowering nitrogen rates below the economic optimum (N-opt) offers little environmental benefit but increases the risk of reduced yields and profitability. It highlights regenerative practices such as optimised nutrient management, crop rotations, cover cropping, and organic amendments can buffer yield losses and improve grain quality by enhancing soil fertility and nitrogen-use efficiency. *Conclusions:* The report warns that cutting chemical nitrogen allowances alone risks yield and profitability penalties. **However, regenerative practices—cover crops, rotations, organic amendments, and precision nutrient management—can mitigate these risks, sustain yields, and improve grain quality**.

Nabuurs, G. and Mrabet, R.	2022	Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)	Specific crop research not mentioned.	Cover cropping and green manures, crop rotation, reduced / conservation tillage, agroforestry, organic amendments, nutrient management.	Grain yield.	The report highlights regenerative agriculture practices such as cover cropping, crop rotations, reduced tillage, agroforestry, organic amendments, and improved nutrient management and the role these practices have in climate change mitigation. These practices are shown to enhance soil carbon sequestration, nutrient cycling, and resilience, which can stabilise or increase grain yields and **improve grain quality (protein content, reduced contamination, better malting/baking suitability)** when implemented effectively. *Conclusions:* The report focus' on the ability of regenerative agriculture to reduce greenhouse gas emissions. The report is written from a global perspective but clearly specifies that the success of the system depends on local adaptation, timing, and integration into broader farming systems.

Brown, I. and Matthews, R.	2012	Summary of research relevant to adaptation to climate change in the agricultural sector in Scotland	Cereals (barley and wheat) and potatoes.	Cover cropping, crop rotations, reduced tillage, soil management, and variety breeding.	Grain yield.	The research synthesis shows that regenerative practices—cover crops, rotations, reduced tillage, resilient breeding, and organic amendments—are central to climate adaptation. However, the report focus' on climate adaptation with little mention of grain quality other than to maintain grain yields. *Conclusions:* Although regenerative practices are found to provide methods for climate adaptation for farmers, **the impacts that these practices have on grain quality is not given sufficient consideration**.
Thoman, R., Bhogal, A., Kendle, S. and Bailey, G.	2024	NiCCs – Nitrogen release from Cover Crops, 2021- 2023 FINAL	Cover Crop, spring oats, spring barley.	Cover crop and cover crop destruction method.	Grain yield. Specific weight (oats). Protein content (barley).	Where cover crops were destroyed with glyphosate, the spring barley yield was maintained or increased and the spring oat specific weight increased. However, where cover crops were destroyed using a mechanical roller during frost, yield was reduced for both crops. No cover crops (winter fallow) were found to produce lower specific weight oats and increase the barley protein content variability. *Conclusions:* The study found that cover crops can reduce nitrate leaching by up to 90%. However, **the termination method had a large impact on the yield and quality of the following crop**.

Burnett, F.	2024	AHDB	Spring barley, winter wheat.	Cover crop (destruction methods). Reducing chemical inputs (fertiliser), yield and quality data for the fertiliser trial not available.	Grain yield.	This field trial investigated the impact cover crop termination had on spring barley yield. An oat pea and bean cover crop was grown. Several elements were measured, including cover crop establishment, disease, weed burden and yield. Integrated into the 3 termination methods (grazing, spraying, no cover crop), the spring barley drilling date was also altered (standard, +7-10 days, -7-10days). *Conclusions:* **The yield from the grazed treatment area outperformed the other cover crop termination methods** by 0.5t/ha.

Remarks from scientific literature

- The limited number of studies and their inconsistency do not allow to reach definitive conclusions on the causal-relationships between regenerative practices and grain quality.
- There are interactions between practices underpinning different regenerative principles such as reduce tillage, green manure and livestock integration (Çiçek et al. 2014; Hu et al. 2020). For instance, no-tillage practice can mitigate soil degradation induced by grazing and enhance grain quality.
- Urea input from livestock can reduce grain quality in barley (Hu et al. 2020).
- No tillage and minimum tillage can reduce N availability and grain proteins in wheat (McConkey et al. 2002).
- Reducing tillage can affect the uptake of micronutrients (e.g. lower Cu and Zn in direct drill (Carter and Gupta 1997)).
- Different agricultural practices can affect mycotoxin contamination in wheat grain. While lower mycotoxin contamination has been reported in organic-farming compared to conventional-farming (Bernhoft et al. 2010), reduced tillage has been associated with an increase in fusarium infestation and mycotoxin contaminations in wheat-grain (Edwards 2004; Champeil et al. 2004).
- Cover crop termination method and timing determine whether benefits to soil health translate into higher yields and better grain quality (Jenkins and Randall 2025, Thoman et al. 2024, Burnett 2024).

Appendix 1 - Methods

A comprehensive search, using multiple key words, was used to capture an un-biased sample of literature. The search strategy was developed to identify both peer-reviewed and grey literature. Given the timescale of this project, initial search for peer-reviewed literature has been limited to Scopus (https://www.scopus.com), a large, multidisciplinary abstract and citation database for peer-reviewed research literature. The search string was adapted to the syntax of source database with a record of each search made.

The search string was formulated by the project team and using reiterated scoping searches to test keywords for specificity and sensitivity using the online database Scopus. Subject experts were also consulted to ensure all key and relevant terms were used within the search string. The results of an initial scoping search, and comments from subject experts, informed the final search string.

Search string

The search string (Table 2) is the combination of keywords falling into four categories: (i) Crops (ii) Grain-quality parameters (iii) Farming practices and (iv) climate.

Table 2

Category	Keywords
Crop	"malting barley" OR "spring barley" OR barley OR "Hordeum vulgare" OR wheat OR "Triticum aestivum") NOT rice
Grain-quality parameters	"grain quality" OR malt OR "protein content" OR "grain protein" OR "diastatic power" OR yield OR "Hagberg falling number" OR "falling number" OR "extract yield" OR "beta-glucan" OR glucan OR screenings OR size OR width OR "thousand grain weight" OR "TGW" OR germination OR screen* OR mycotoxin OR DON OR deoxynivalenol
Farming practices	"regenerative agriculture" OR "regenerative farming" OR conservation OR "regenerative practice" OR "conservation agriculture" OR "conservation tillage" OR tillage OR “Shallow till” OR "reduced till" OR "minimum till" OR “min till” OR “min-till” OR "no till" OR "no-till" OR "zero till" OR tillage OR livestock OR “living root” OR “ground cover” OR disturbance OR "cover-crop" OR "catch crop" OR "green manure" OR “protect soil” OR "diverse rotation" OR "crop rotation" OR intercrop* OR agrofor* OR “green manure” OR “CO2 equivalent” OR "crop drivers" OR "rotation drivers" OR agroecolog OR "agroecological" OR "organic farming"
Climate	"Scotland OR Scottish" OR "Northern England" OR "North England" OR "Northumberland OR Cumbria" OR "Ireland" OR "Irish" OR "Denmark" OR "Danish" OR "Sweden" OR "Swedish" OR "Norway" OR "Norwegian" OR "Iceland" OR "Icelandic" OR "New Zealand" OR "Canada" OR "maritime climate" OR "cool temperate" OR "temperate maritime" OR Cfb OR "Cfb climate" OR "oceanic climate" OR "UK"

Selection of studies

Search results were exported from Scopus for title and abstract screening using a standardised form. Publications presenting information on grain-quality under regenerative practices were selected as potentially eligible studies. All potentially eligible studies were screened by two independent reviewers who read the full papers to confirm eligibility and extract the following data in a standardised form:

- Authors full names
- Title
- Year
- Journal
- DOI
- Abstract
- Crop(s)
- Regenerative practice(s)
- Grain-quality parameters
- Outcomes

Grey literature

The project team compiled a comprehensive list of potential sources of grey literature including levy funded organisations, research institutions and universities. Each organisations website which had been identified as a potential source was visited and searches within the organisation's site conducted using search terms defined for the scientific paper review. Due to limited findings, including grain quality information, the search was widened to include grey literature from across the UK and to include research which investigated regenerative agricultural practise in relation to yield. Relevant papers were listed before being evaluated for relevance. Grey literature within the final review were included due to their geographic location, specific reference to grain quality, comparison of grain yield, or wider discussion on the impacts that regenerative agriculture may have on the quality or consistency of grain supply.

Risk of Bias

Studies were assessed for risk of bias using criteria adapted for agronomic field trials:

- Randomisation and allocation (where applicable)
- Replication and plot size adequacy
- Baseline comparability
- Completeness of outcome data (missing years/data)
- Appropriateness of statistical analysis (repeated measures, blocking)
- Selective reporting of outcomes

Literature used

In total, 161 papers were highlighted from the Scopus search and subsequently screened for potential inclusion in the review using abstract screening. Publication dates ranged from 1984 to 2025 (**Fig 2**) with 93 papers originating from Canada, 13 papers from the UK and a further 13

papers from Scandinavian countries (Denmark, Sweden and Norway) (**Fig. 3**). Of the 161 abstracts screened, 43 papers, which fully complied with the selection criteria, were selected to be reviewed fully. Peer-reviewed and grey literature were analysed separately.

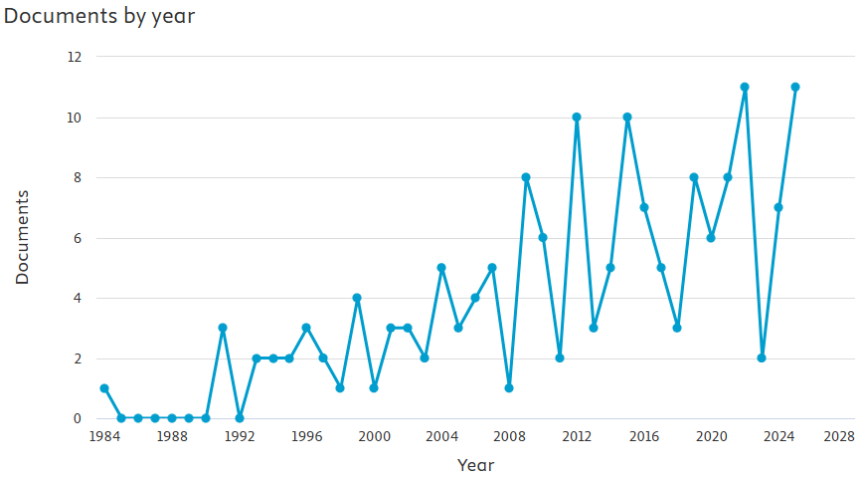


Figure 2. Publication date for peer reviewed papers highlighted for screening following a systematic search of the Scopus database.

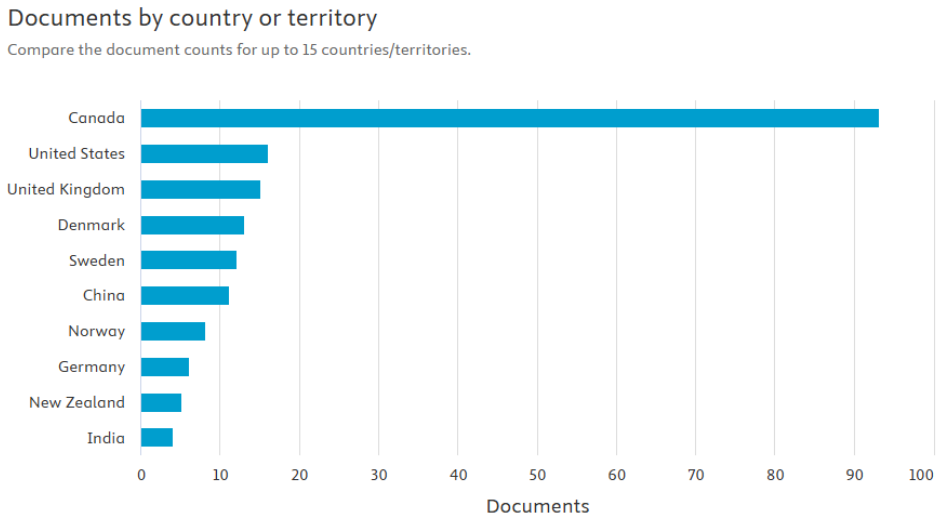


Figure 3. Publication country/territory of papers highlighted for screening following a systematic search of the Scopus database.

The selected peer-reviewed papers (**Appendix 2**) investigated five regenerative practices: "**Reduced tillage**" (13 papers; Table 3) "**Cover crops and green manure**" (5 papers; Table 4), "**Crop and rotation diversification**" (5 papers; Table 5), "**Mixed farming**" (1 paper; Table 6), and "**Reduced synthetic inputs – organic systems**" (6 papers; Table 7). Two literature reviews, summarising the effects of different agricultural-practices on mycotoxin contamination, were also included (Table 8). It should be noted that some studies consider the effect of combined practices. For instance, Çiçek et al. (2014) evaluated grazed and ungrazed green manures, and Hu et al. 2020 investigated the interaction between tillage and grazing. Selected **grey literature** (**Appendix 3)** included nine reports (Table 9) from public bodies (e.g. UK Parliament Post) and non-governmental organisations (e.g. British Ecological Society). Most of these reports highlight the wider benefices and knowledge-gaps considering "regenerative agriculture as a system

approach" and its potential in agricultural transition toward sustainable practices (e.g. reports from British Ecological Society and IPCC). However, reports on specific practices (e.g. cover crops) were also identified and information extracted (e.g. Burnett et al. 2024 report on termination methods for cover crops).

Expert opinion and results from literature review

The uptake of regenerative agricultural principles in Scotland is not documented, therefore, the extent and information on the adoption of practices implemented on farm is largely unknown. Nevertheless, regenerative principles are often discussed within farmer groups or levy boards in addition to discussions between advisors and farmers, either in isolation or in combination with general integrated crop management approaches. The following section is opinion based and details the perceived uptake and extent of regenerative agriculture principles in Scotland. Furthermore, it expands on the potential for practises to be implemented in the future. At present, there is limited data and knowledge of the impact regenerative principles have on the yield of crops, with even less robust information known about grain quality effects.

Appendix 2 – Peer-reviewed scientific literature - Selected papers

Authors	Year	Title	Abstract	Journal	DOI
Bernhoft, A.; Clasen, P.-E.; Kristoffersen, A.B.; Torp, M.	2010	Less Fusarium infestation and mycotoxin contamination in organic than in conventional cereals	A total of 602 samples of cereals, consisting of organically and conventionally produced barley, oats and wheat, were collected at harvest during 2002-2004 in Norway. Organic and conventional cereals were sampled in comparable numbers regarding cereal species, localisation and harvest time, and analysed for Fusarium mould and mycotoxins. Fusarium infestation and mycotoxin content were dependent on cereal species and varied year-by-year. However, in all cereal species, Fusarium infestation and levels of important mycotoxins were significantly lower when grown organically than conventionally. Concerning the most toxic trichothecenes, HT-2 and T-2 toxin, lower concentrations were found in organic oats and barley. Wheat was not contaminated by HT-2 and T-2, but lower concentrations of deoxynivalenol (DON) and moniliformin (MON) were found when organically produced. For mycotoxins considered to constitute the main risk to humans and animals in Norwegian cereals, i.e. HT-2 in oats and DON in oats and wheat, the median figures (mean levels in brackets) were as follows: HT-2 in organic and conventional oats were <20 (80) and 62 (117) µ/kg, DON in organic and conventional oats were 24 (114) and 36 (426) µ/kg, and DON in organic and conventional wheat were 29 (86) and 51 (170) µ/kg, respectively. Concentrations of HT-2 and T-2 in the samples were strongly correlated (r=0.94). Other mycotoxins did not show a significant correlation to each other. Both HT-2 and T-2 concentrations were significantly correlated with infestation of F. langsethiae (r=0.65 and r=0.60, respectively). Concentrations of DON were significantly correlated with F. graminearum infestation (r=0.61). Furthermore, nivalenol (NIV) was significantly correlated with infestation of F. poae (r=0.55) and MON with F. avenaceum (r=0.37). As lower Fusarium infestation and mycotoxin levels were found in organic cereals, factors related to agricultural practice may reduce the risk of contamination with Fusarium mycotoxins. Studies of these issues will be presented separately. © 2010 Taylor & Francis.	Food Additives and Contaminants	10.1080/19440410 03645761

Brandt, S.	1999	Management practices for black lentil green manure for the semi-arid Canadian prairies	Previous research with lentil (Lens culinaris Medic.) green manure in the semiarid prairies of western Canada has indicated that water use by the green manure crop often reduces grain yield of the succeeding cereal crop compared to those obtained after conventional summer fallow. In this study, we evaluated several green manure management practices that have potential to trap snow and enhance overwinter soil water recharge. These practices included: using herbicides to halt the growth of the green manure crop thus eliminating the need for soil incorporation, planting mustard (Sinapis alba L.) strips after incorporation, and leaving standing strips of non-incorporated lentil. Our results showed that none of the green manure management strategies increased wheat (Triticum aestivum L.) yield or grain protein concentration compared to wheat grown on conventional summer fallow. Leaving strips of standing lentil during bud stage incorporation provided barriers for wind erosion protection, while not decreasing wheat yield or protein content. Glyphosate or 2,4-D amine applied at bud stage of the lentil, and without soil incorporation, reduced available soil N. However, 2,4-D did not halt plant growth and water use quickly enough to avoid reducing yield of the succeeding wheat crop, while glyphosate generally halted water use more rapidly. The inability of the green manure management strategies to increase wheat yields over that obtained from conventional summer fallow was because the soil rooting zone is typically filled to capacity with water by this latter practice under the prevailing soil and climatic conditions. If green manuring is practised, early incorporation with lentil leave strips is the most promising management system. However, even with improved water management practices, green manuring did not demonstrate a consistent advantage over summer fallow, which may be required to offset the added economic costs required to enact this practice.	Canadian Journal of Plant Science	10.4141/P97-091
Brandt, S.	1996	Alternatives to summer fallow and subsequent wheat and	Several alternative options to summer fallow are feasible on the Dark Brown soils of the Canadian prairies. These include recropping to cereal or pulse crops, as well as use of summer fallow substitute crops, such as legume green manures. The objective of this study was to evaluate these options for their impact on the productivity of subsequent crops.	Canadian Journal of Plant Science	10.4141/cjps96-041

		barley yield on a Dark Brown soil	Green- manure lentil (Lens culinaris Medic.), incorporated at either the bud or full-bloom stage of growth, field pea (Pisum sativum L.), grain lentil, and wheat (Triticum aestivum L.) grown as grain were compared with conventional summer fallow for their impact on yield of a succeeding wheat crop and of barley (Hordeum vulgare L.) grown the year after wheat on a Dark Brown Chernozemic soil at Scott, Saskatchewan. During the 5-yr period, 1984-1988, above-ground dry-matter production of green-manure lentil averaged 1500 kg ha-1 at the bud stage of growth but more than doubled to 3170 kg ha-1, by full bloom. Grain yield of field pea averaged 1470 kg ha-1 while that of grain lentil, unfertilized wheat, and N-fertilized wheat averaged 1220, 1290 and 1490 kg ha-1, respectively. Considerable year-to-year yield variation occurred with all crops, variability being greatest for lentil. Yield of wheat grown after lentil green manure was similar to yield of wheat on summer fallow (2340 kg ha-1) during each of the 5 yr for both early (2360 kg ha-1) and late (2250 kg ha-1) incorporation. Wheat yield after pea (2210 kg ha-1) or grain lentil (2080 kg ha-1) was reduced in 1987, but it was equal to wheat yield after summer fallow during the remaining 4 yr. Yield of wheat on wheat stubble, whether fertilized with N (1830 kg ha- 1) or not (1610 kg ha-1), was generally lower than on summer fallow. Yield of barley grown the following year was generally unaffected by summer fallow or summer fallow substitute treatments. The higher value and similar productivity of pea and grain lentil, compared with wheat, combined with their favourable impact on subsequent wheat yield, should make these crops attractive alternatives to summer fallow. On fields unsuited to pea or grain lentil production, lentil green manures may be a suitable alternative to summer fallow because they should reduce soil degradation, although lentil green manures leave little residue to protect against soil erosion where thorough incorporation is practised. Summer fallow or green manure incorporated early or late generally resulted in greater available soil water and N for a succeeding crop than did grain lentil, pea or wheat.		

Brozyna, M.A.; Petersen, S.O.; Chirinda, N.; Olesen, J.E.	2013	Effects of grass-clover management and cover crops on nitrogen cycling and nitrous oxide emissions in a stockless organic crop rotation	Nitrogen (N) supply in stockless organic farming may be improved through use of grass-clover for anaerobic digestion, producing biogas and digested manure for use as fertiliser in the crop rotation. We studied the effects of grass-clover management on N cycling, nitrous oxide (N<inf>2</inf>O) emissions and cash-crop yields in an organic arable crop rotation on a sandy loam soil in a cool temperate climate. The four-course crop rotation included spring barley (with under sown grass-clover), grass-clover, potato and winter wheat (with under sown cover crop). Two fertilisation treatments were compared: "-M" where plant material from grass-clover cuts was left in the field to decompose and no fertiliser or manure was applied to any crop in the rotation; and "+M" where plant material from grass-clover cuts was harvested and equivalent amounts of N in digested manure used for fertilisation of cash crops in the rotation (spring barley, potato and winter wheat); actual digestion of grass-clover cuttings was not possible, instead digested pig manure was used as substitute for digested grass-clover. Nitrous oxide fluxes were monitored between April 2008 and May 2009. In general, application of digested manure had little or no effect on N<inf>2</inf>O emissions. Periods of high N<inf>2</inf>O emissions coincided with cover crop and grass-clover residue turnover, with little added effect of digested manure application. Annual N<inf>2</inf>O emissions did not vary between fertilisation treatments, but the +M treatment had cash crop dry matter yields that were 14% higher than in the -M treatment, and cash crop N yields were increased by 40%. The results show that reallocation of nutrients from grass-clover to cash crops following anaerobic digestion can help solve problems with low N availability. However, issues remain regarding N<inf>2</inf>O from cover crops and grass-clover in spring. © 2013 Elsevier B.V.	Agriculture, Ecosystems and Environment	10.1016/j.agee.2013.09.013

Bruun, E.W.; Müller-Stöver, D.; Pedersen, B.N.; Hansen, L.V.; Petersen, C.T.	2022	Ash and biochar amendment of coarse sandy soil for growing crops under drought conditions	Appropriate soil amendments may increase plant available water and crop yields on coarse sandy soils under drought conditions. In this study, we applied straw ash or straw biochar from gasification to a Danish coarse sandy subsoil to assess the effects on soil water retention, evapotranspiration and crop yields. Spring barley (2016, 2017) and winter wheat (2018) were grown over three years in columns containing 25cm of organic matter-rich topsoil, 80 cm of amended coarse sandy soil (1.5%, 3%, 6% wt. ash or 1% wt. biochar or control soil) and 45 cm of un-amended subsoil. Precipitation, evaporative demands and soil moisture were recorded across the growth seasons, with 2018 having severe drought conditions. This year evapotranspiration levels increased with increasing ash and biochar content (by 54% and 33% for the 6% ash- and 1% biochar-amended soils, respectively), and plant dry matter increased by 18% in both the 1% biochar- and 6% ash-treated soils compared to the untreated control. A linear relationship was established between in situ field capacity and ash dosage (R2=.96), showing an increase of 2.2% per percentage (wt.) of ash added, while the 1% biochar treatment increased the capacity by 3.5%, indicating a higher efficiency than for ash. However, we did not find significant positive effects on grain yields. The results show that ash and biochar have the potential to significantly increase soil water retention, evapotranspiration and total dry matter yield in drought conditions, but that this may not correspond to an increase in grain yield. © 2021 British Society of Soil Science.	Soil Use and Management	10.1111/sum.12783

Bullied, W.J.; Entz, M.H.	1999	Soil water dynamics after alfalfa as influenced by crop termination technique	Because of their deep roots and high-water demand, alfalfa (Medicago sativa L.) hay crops can reduce water available to crops following in the rotation. Recharging the soil water profile after alfalfa is, therefore, a high priority in dryland cropping systems. The objective of this study was to investigate effects of alfalfa crop termination date (late June, early August, and in spring immediately before spring wheat seeding) and method (herbicides, tillage, and herbicides plus tillage) on soil water conservation, and establishment, yield, and water use efficiency (WUE) of a following spring wheat (Triticum aestivum L.) crop. Experiments were conducted over 5 site-years in a subhumid region of western Canada. Herbicide termination resulted in greater total water recharge and a faster rate of water recharge than treatments involving tillage. Greater efficiency of soil water recharge for herbicide termination after the first hay harvest (late June) appeared to cause deep water percolation at one site. Delaying termination until after the second hay harvest (early August) did not reduce soil water availability at spring seeding of the following wheat crop, but increased reliance on overwinter soil water recharge. Delaying herbicide treatment until spring reduced water at seeding and wheat yields in some cases. Compared with treatments involving tillage, herbicide treatments resulted in higher levels of groundcover (i.e., greater soil erosion control), higher WUE, and higher grain yields. Herbicide termination after the second hay harvest produced the most favourable overall outcome; better than the traditional approach of tillage after the first hay harvest.	Agronomy Journal	10.2134/agronj1999.00021962009100020019x
Carter, M.R.; Gupta, U.C.	1997	Micronutrient concentrations in barley and soybean under minimum tillage on podzolic soils in a cool climate	Micronutrients can be limiting for crop production and quality in fine sandy loam Podzolic soils in the cool, humid climate of Atlantic Canada. This study was conducted to determine the effect of minimum tillage practices, in three long-term animal feed crop rotations, on micronutrient (B, Cu, Zn, Mn, Fe and Mo) content and grain quality of spring barley (Hordeum vulgare L.) and soybean (Glycine max L. Merrill). Reductions in soil tillage had various effects on micronutrient concentration in plant parts, especially for Cu, Zn, Mn, and Mo, which were probably related to pH changes at the soil surface. Grain micronutrient concentrations, however, for crop yield potential tended	Acta Agriculturae Scandinavica Section B: Soil and Plant Science	10.1080/09064719709362432

			to be in the sufficiency range and were not limiting for crop growth or feed quality. Evidence suggesting a decline in Mo concentration over time underlines the need for periodic assessment of micronutrient assimilation in conservation tillage systems. © 1997 Scandinavian University Press.		
Champeil, A.; Doré, T.; Fourbet, J.F.	2004	Fusarium head blight: Epidemiological origin of the effects of cultural practices on head blight attacks and the production of mycotoxins by Fusarium in wheat grains	Fusarium head blight is an ancient disease and is very common throughout the world. In this article, we review current knowledge concerning the effects of cultural practices on the development of head blight and the production of toxins in the field. The qualitative effects of these practices on the severity of the disease and/or the production of toxins are in the process of being elucidated but, in many cases, detailed studies have not yet been carried out or conflicting results have been obtained. However, it should be noted that these effects have not yet been quantified. Three different cultural practices are today considered to be of prime importance for combating this disease and the production of mycotoxins: deep tillage, the choice of the preceding crop in the rotation and the choice of appropriate cultivar, as varietal effects exist. © 2004 Elsevier Ireland Ltd. All rights reserved.	Plant Science	10.1016/j.plantsci.2004.02.004

Çiçek, H.; Thiessen Martens, J.R.T.; Bamford, K.C.; Entz, M.H.	2014	Forage potential of six leguminous green manures and effect of grazing on following grain crops	There is a need to design intensive cropping systems that can reap multiple benefits from annual forages including animal feed, soil fertility and weed control. Considering pea/oat (Pisum sativum cv. 40-10/Avena sativa cv. Legget) as a standard green manure, this study investigated the productivity, weed competitiveness, utilisation and nitrogen (N) benefit from grazed and ungrazed green manures to spring wheat (Triticum aestivum cv. Waskada) and fall rye (Secale cereale cv. Hazlet). A set of 3-year experiments was carried out in Carman, Manitoba, Canada in 2009, and was repeated in 2010 and 2011. Green manures were grazed by 2-3 ewes and 2-5 lambs for 24 h (1111-1667 sheep days per ha). Averaged over experiments pea/oat mix, hairy vetch (Vicia villosa L.) and sweetclover (Melilotus officinalis cv. Norgold) above-ground dry matter (DM) production were 5036, 5032 and 4064 kg ha-1, respectively. Lentil (Lens culinaris cv. Indianhead), a mixture of seven species and soybean (Glycine max cv. Prudence) produced the least amount of DM over 3 years; 3589, 3551, 3174 kg ha-1, respectively. Pea/oat and hairy vetch were the most weed-competitive species and averaged over 3 years, contained less than 15% weed DM. Utilization of green manures by grazing animals varied little among species across years and ranged from 28 to 86% for individual species and years. When combined across experiments grazing increased N availability to the wheat crop. The grazing effect was significant for wheat DM production, N uptake and grain N, but not significant for yield across experiments. Averaged over 3 years, wheat took up 107 kg N ha-1 from grazed plots versus 98 kg N ha-1 from ungrazed plots. A significant species × management interaction for total (wheat + fall rye) N uptake in 2009 indicated that increasing the proportion of legumes in the green manure increased N benefit from grazing. Fall rye productivity was not affected by grazing. We recommend pea/oat and hairy vetch as two green manure species to enhance the overall system performance to achieve high level of DM production, good weed competition, utilization by sheep and provision of N benefit to the following wheat and fall rye crops. © © 2014 Cambridge University Press.	Renewable Agriculture and Food Systems	10.1017/S1742170514000349

Cope, J.E.; Newton, A.C.	2025	Performance of elite and heritage germplasm in barley genotype mixtures: effects on yield and disease under diverse management scenarios	Genotype mixtures are multiple crop lines grown together to improve yield, stability, and disease control by utilizing different genetic and morphological traits. Incorporating heritage germplasm may enable exploitation of low input adaptation traits while retaining the high yield of elite modern cultivars. However, the effects of nutrient application, sowing density, and disease management on competition/facilitation dynamics in genotype mixtures with diverse germplasms, such as landraces, remain largely unknown. A set of complimentary plot experiments, undertaken in the arable cropping area of the east of Scotland, assessed genotype mixtures using heritage lines and/or elite cultivars of both spring and winter barley. The experimental systems manipulated the sowing densities, mixture composition, nitrogen application, and fungal disease pressure across three different field seasons. Here we show that the advantages of genotype mixtures were highly dependent on the genotypic makeup of the mixture and the environmental conditions in which they are grown, demonstrating complex genotype mixture × environment interactions. Genotype mixture performance in barley is highly dependent on the interaction of genetic composition and management factors. This paper revealed, for the first time, that small amounts of heritage germplasm enhanced yield stability, though overall yields rarely match those of the elite monocultures and no consistent disease reduction was observed. Although barley gains limited benefits from mixing genotypes, our study is able to highlight complex trends in mixture composition and environment that are relevant for crops with greater genotype mixture yield benefits. © The Author(s) 2025.	Agronomy for Sustainable Development	10.1007/s13593-025-01049-8

Edwards, S.G.	2004	Influence of agricultural practices on fusarium infection of cereals and subsequent contamination of grain by trichothecene mycotoxins	Fusarium head blight (FHB) of small grain cereals and ear rot in maize are significant diseases across the world. Infection can not only result in reduced yield as a result of shrunken grains but also result in reduced milling and malting quality and the contamination of grains with mycotoxins. Mycotoxins are hazardous to animal and human health. Therefore, guidelines and legislation are in place, or under consideration, in most countries to protect consumers and animal welfare. As fusarium mycotoxins are produced within the growing crop, it is important to understand how agricultural practices affect mycotoxin contamination of grain. Such information could then be used to determine guidelines on "Good Agricultural Practice" (GAP) to minimise the mycotoxin contamination of cereal products. Evidence is provided to show the importance of choice of cultivar, crop rotation, soil cultivation, fertiliser and the chemical and biological control of insects, weeds and fungi. © 2004 ILSI. Published by Elsevier Ireland Ltd. All rights reserved.	Toxicology Letters	10.1016/j.toxlet.2004.04.022
Gao, X.; Grant, C.A.	2012	Cadmium and zinc concentration in grain of durum wheat in relation to phosphorus fertilisation, crop sequence and tillage management	Field experiments were conducted at two locations in Manitoba, Canada, to determine the effect of crop rotation, phosphorus (P) fertilisation and tillage on grain yield and grain concentrations of Cd and Zn in durum wheat (Triticum durum L.). Compared to conventional tillage (CT), reduced tillage (RT) management decreased grain Cd and increased grain yield and grain Zn in half of the site-years. The type of preceding crops of spring wheat-flax or canola-flax had little influence. Rate and timing of P application had little effect on grain Cd, but increasing P rate tended to decrease grain Zn. No interactive effect was detected among tested factors. Grain Zn was not related to grain Cd, but positively to other nutrients such as Fe, Mn, P, Ca, K, and Mg. Both grain Zn and Fe correlated positively with grain protein content, suggesting protein may represent a sink for micronutrients. The study suggested that the tillage management may have beneficial effects on both grain yield and quality. Phosphorus fertiliser can remain available for subsequent crops and high annual inputs in the crop sequence may decrease crop grain Zn. Understanding the environment is important in	Applied and Environmental Soil Science	10.1155/2012/817107

			determining the impact of agricultural management on agronomic and nutrient traits. © 2012 Xiaopeng Gao and Cynthia A. Grant.		
Gao, X.; Grant, C.A.	2011	Interactive effect of N fertilization and tillage management on Zn biofortification in durum wheat (Triticum durum)	A 3-yr field study was conducted at two locations in southwestern Manitoba, Canada, to determine the interactive effect of application of four sources of N fertilizer and two tillage management systems on grain Zn concentration of durum wheat. There was a significant year-to-year variation in grain yield and grain Zn concentration, indicating a strong environmental influence. Soil type also had a dominating effect, with grain Zn concentration generally being higher at the clay loam location than the fine sandy loam location, reflecting the native soil Zn status. Tillage management showed little influence on grain Zn, suggesting that reduced tillage practices can be adopted by local farmers without decreasing mineral concentrations in grain. Compared with the control treatment, which did not receive extra N fertiliser, N fertilisation at 60 kg ha-1 decreased grain Zn concentration in 4 of 6 site-years. Grain Zn accumulation was, however, generally not affected by extra N fertilisation, despite a positive fertilisation effect on grain yield. The four N sources did not differ in their effect on grain yield and grain Zn, indicating that at the rate of N applied there were no differential fertiliser source effects on Zn availability. The results of the present study suggest that for wheat production on Canadian prairies, a regular N fertilisation rate using the currently registered cultivars is not likely to produce wheat grain that meets the recommended dietary allowance for Zn. Application of Zn fertiliser, in combination with optimum N fertilisation or other agronomic practices that can increase grain Zn, is required to produce improved grain quality for human health.	Canadian Journal of Plant Science	10.4141/cjps2011-026
Hu, W.; Beare, M.; Tregurtha, C.; Gillespie, R.; Lehto, K.; Tregurtha, R.; Gosden, P.; Glasson, S.; Dellow, S.;	2020	Effects of tillage, compaction and nitrogen inputs on crop production and nitrogen losses following	Soil compaction from livestock treading during winter grazing of forage crops on cultivated soils may be harmful to subsequent crop production and nitrogen (N) loss. This study focussed on determining: (1) how compaction and high inputs of N from livestock urine (urea) during winter grazing affect subsequent crop production and N loss and (2) whether establishing winter-grazed forage crops with no-tillage (NT) can mitigate potential adverse effects on subsequent crop production and N loss. A field trial was conducted on a Templeton silt loam soil in	Agriculture, Ecosystems and Environment	10.1016/j.agee.2019.106733

George, M.; Tabley, F.; Qiu, W.; Baird, D.		simulated forage crop grazing	Canterbury, New Zealand from April 2016 to February 2017, comprising of forage crop (oat), grazing, and subsequent crop (barley) phases. The forage crop phase represented the production of forage oat crops established using NT or intensive tillage (IT) in autumn. The grazing phase was simulated by removal of the forage crop, followed by simulated grazing that comprised five compaction levels (0–261 kPa) and two urea-N treatments (0 versus 400 kg N ha−1). A subsequent barley crop was sown following shallow (<15 cm) cultivation of soil in spring. Results indicated relatively little net effect of compaction on crop yield and total N losses over the combined grazing and barley phases. However, moderate compaction (180–220 kPa) increased the water use efficiency and grain yield of the subsequent barley crop. Simulated urinary-N (urea) inputs during grazing promoted vegetative growth of barley but restricted its reproductive growth (i.e. grain yield) and increased N loss during the barley phase. The use of NT amplified the adverse effect of simulated urinary-N (urea) inputs on yield and N loss. This suggests that variations in urinary-N inputs should be taken into account when applying fertiliser for subsequent crops. Adoption of NT during forage crop establishment did little to mitigate the effects of compaction on subsequent crop production, but it enhanced crop growth and water use efficiency in the early stages of the subsequent barley crop without sacrificing the final grain yield. In addition, NT crop had a significantly lower screenings than IT at final harvest. Compared with IT, NT increased N loss during the grazing phase but reduced N loss during the barley phase, resulting in no significant net effect of tillage on total N losses over the two phases. However, the lower cost of NT crop establishment and greater marketable grain yield as well as the reduced risk of soil compaction and N<inf>2</inf>O emissions reported in previous studies provide agronomic and environmental incentives to adopt NT in forage cropping systems. Our study also highlighted important temporal differences in the effects of agricultural management factors (i.e. tillage, compaction, and urinary-N inputs) on crop production and N losses to the environment. © 2019 Elsevier B.V.		

Hummel, J.D.; Dosdall, L.M.; Clayton, G.W.; Turkington, T.K.; Lupwayi, N.Z.; Neil Harker, K.; O'Donovan, J.T.	2009	Canola-wheat intercrops for improved agronomic performance and integrated pest management	Intercropping can enhance yields and reduce pest infestations, but investigations of intercropping regimes using crop species common to the large-scale monoculture production systems of western Canada have not examined these diverse elements. Inter-crops of canola (Brassica napus L.) and wheat (Triticum aestivum L.) were established at three sites in Alberta, Canada in 2005 and 2006 to determine interactions between intercropping regimes and crop grain and biomass yield, crop quality characteristics, soil microbial community biomass and diversity, flea beetles (Phyllotreta spp., Coleoptera: Chrysomelidae), and wheat leaf diseases. The study also investigated effects on flea beetles and soil microbial communities of a canola seed treatment containing a neonicotinoid insecticide and fungicides. Crop yields were comparable between intercrops and monocultures of canola and wheat. Crop quality characteristics and flea beetle feeding damage to canola seedlings had variable responses to intercropping. Flea beetle feeding was reduced with the inclusion of the seed treatment by between 1 and 20% damaged leaf area, although only one site-year had damage levels great enough to overcome plant compensatory abilities in untreated plots. The first true-leaf stage of canola development experienced the greatest flea beetle damage. Proportions of pathogen-infected wheat leaf tissue were up to 2.5 times greater in intercrops than wheat monocultures but tended to decrease as the proportion of canola in the intercrops increased. Soil microbial parameters were unaffected by factors investigated. Although intercrop yields approximated those of monocultures, additional benefits of canola-wheat intercrops determined in this study appear insufficient to recommend this system for widespread adoption. © 2009 by the American Society of Agronomy.	Agronomy Journal	10.2134/agronj2009.0032

Iqbal, M.; Semagn, K.; Cerón-Rojas, J.J.; Crossa, J.; Jarquín, D.; Howard, R.; Beres, B.L.; Strenzke, K.; Ciechanowska, I.; Spaner, D.	2022	Identification of Spring Wheat with Superior Agronomic Performance under Contrasting Nitrogen Managements Using Linear Phenotypic Selection Indices	Both the Linear Phenotypic Selection Index (LPSI) and the Restrictive Linear Phenotypic Selection Index (RLPSI) have been widely used to select parents and progenies, but the effect of economic weights on the selection parameters (the expected genetic gain, response to selection, and the correlation between the indices and genetic merits) have not been investigated in detail. Here, we (i) assessed combinations of 2304 economic weights using four traits (maturity, plant height, grain yield and grain protein content) recorded under four organically (low nitrogen) and five conventionally (high nitrogen) managed environments, (ii) compared single-trait and multi-trait selection indices (LPSI vs. RLPSI by imposing restrictions to the expected genetic gain of either yield or grain protein content), and (iii) selected a subset of about 10% spring wheat cultivars that performed very well under organic and/or conventional management systems. The multi-trait selection indices, with and without imposing restrictions, were superior to single trait selection. However, the selection parameters differed quite a lot depending on the economic weights, which suggests the need for optimising the weights. Twenty-two of the 196 cultivars that showed superior performance under organic and/or conventional management systems were consistently selected using all five of the selected economic weights, and at least two of the selection scenarios. The selected cultivars belonged to the Canada Western Red Spring (16 cultivars), the Canada Northern Hard Red (3), and the Canada Prairie Spring Red (3), and required 83–93 days to maturity, were 72–100 cm tall, and produced from 4.0 to 6.2 t ha−1 grain yield with 14.6–17.7% GPC. The selected cultivars would be highly useful, not only as potential trait donors for breeding under an organic management system, but also for other studies, including nitrogen use efficiency. © 2022 by the authors.	Plants	10.3390/plants11141887

Izaurralde, R.C.; Juma, N.G.; McGill, W.B.; Chanasyk, D.S.; Pawluk, S.; Dudas, M.J.	1993	Performance of conventional and alternative cropping systems in cryoboreal subhumid central alberta	A 3-year field study (1986–88) was conducted in central Alberta to discover how diverse soil-plant systems function under cryoboreal subhumid conditions. Barley, fescue, faba (field) bean and a barley/field pea intercrop were grown continuously on different soils at Ellerslie and Breton using two distinct tillage methods. The agronomic performance, weed—crop interactions and below-ground productivity of these cropping systems were examined. The main findings were as follows: different soil properties did not affect yields of barley, barley/field pea and fescue fertilized with N and P; silage yield of faba bean at Breton was greater than at Ellerslie; barley/field pea and faba bean could be grown without tillage at Ellerslie; barley/field pea plots had the lowest weed counts; fescue root biomass was greatest at all depths followed by faba bean and barley; and soil properties appeared not to induce differences in root production of a cereal, an annual forage legume and a perennial grass. Increasing the use of annual legumes into rotations, either as sole crops or as intercrops with cereals, may be a viable alternative to continuous cereal cropping because annual legumes contribute N through biological N fixation, reduce weed competition and increase the input of root mass in soil. © 1993, Cambridge University Press. All rights reserved.	Journal of Agricultural Science	10.1017/S0021859600073561
Kröbel, R.; Campbell, C.A.; Zentner, R.P.; Lemke, R.L.; Desjardins, R.L.; Karimi-Zindashty, Y.	2012	Effect of N, P and cropping frequency on nitrogen use efficiencies of spring wheat in the Canadian semi-arid prairie	Knowledge of nitrogen use efficiency (NUE) is useful for determining fertiliser requirements. We used balance and difference methods to determine the effect of N and P fertiliser on nitrogen use efficiencies for continuous wheat (Triticum aestivum L.) (Cont W) and fallow-wheat-wheat (F-W-W) in a 39-yr crop rotation study conducted on a Brown Chernozem at Swift Current in semi-arid southwestern Saskatchewan. In the balance method, NUE was estimated as yield (Y), or grain N content (GN), divided by either fertilizer N (FN), or FN+soil test N (SN), or FN+SN+growing season net N mineralization (N<inf>min</inf>). Most reasonable results [calculating NUE as either (Y or GN)/(FN+SN+N<inf>min</inf>)] were unaffected by fertiliser or rotation and averaged 10.9 kg grain kg-1 available N and 0.3 kg grain N kg-1 available N, respectively, for the different fertiliser treatments of Cont W and F-W-W. Using the difference method, where check values are	Canadian Journal of Plant Science	10.4141/cjps2011-067

			deducted from treatment values in the numerator, continuous W had greater NUE than F-W-W (roughly 2:1). Variations in NUE were not easily explained in the rotation experiment because of the confounding effect of concurrent increases in available moisture and FN availability in the last decade. However, results from a semi-controlled lysimeter experiment at Swift Current showed that irrigation increased NUE, while increasing FN decreased NUE curvilinearly. Of the methods used to assess NUE, the simplest (Y/FN) was the least accurate. However, data needed for more accurate estimates are less likely to be available to the farming community. © 2011 - Agricultural Institute of Canada.		
Malhi, S.S.; Lemke, R.L.	2007	Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emissions in a second 4-yr rotation cycle	An 8-yr (1998-2005) field experiment was conducted on a Gray Luvisol (Boralf) soil near Star City, Saskatchewan, Canada, to determine the effects of tillage (no-tillage - NT and conventional tillage - CT), straw management (straw retained - R and straw not retained - NR) and N fertilizer (0, 40, 80 and 120 kg N ha-1, except no N to pea (Pisum sativum L.) phase of the rotation) on seed and straw yield, mass of N and C in crop, organic C and N, inorganic N and aggregation in soil, and nitrous oxide (N<inf>2</inf>O) emissions for a second 4-yr rotation cycle (2002-2005). The plots were seeded to barley (Hordeum vulgare L.) in 2002, pea in 2003, wheat (Triticum aestivum L.) in 2004 and canola (Brassica napus L.) in 2005. Seed, straw and chaff yield, root mass, and mass of N and C in crop increased with increasing N rate for barley in 2002, wheat in 2004 and canola in 2005. No-till produced greater seed (by 51%), straw (23%) and chaff (13%) yield of barley than CT in 2002, but seed yield for wheat in 2004, and seed and straw yield for canola in 2005 were greater under CT than NT. Straw retention increased seed (by 62%), straw (by 43%) and chaff (by 12%) yield, and root mass (by 11%) compared to straw removal for barley in 2002, wheat in 2004, and seed and straw yield for pea in 2003. No-till resulted in greater mass of N in seed, and mass of C in seed, straw, chaff and root than CT for barley in 2002, but mass of N and C were greater under CT than NT for wheat in 2004 and for canola in 2005 in many cases. Straw retention had greater mass of N and C in seed, straw, chaff and root in most cases compared to straw removal for barley in 2002, pea in	Soil and Tillage Research	10.1016/j.still.2007.06.011

			2003 and wheat in 2004. Soil moisture content in spring was higher under NT than CT and with R than NR in the 0-15 cm depth, with the highest moisture content in the NT + R treatment in many cases. After eight crop seasons, tillage and straw management had no effect on total organic C (TOC) and N (TON) in the 0-15 cm soil, but light fraction organic C (LFOC) and N (LFON), respectively, were greater by 1.275 Mg C ha-1 and 0.031 Mg N ha-1 with R than NR, and also greater by 0.563 Mg C ha-1 and 0.044 Mg N ha-1 under NT than CT. There was no effect of tillage, straw and N fertilization on the NH<inf>4</inf>-N in soil in most cases, but R treatment had higher NO<inf>3</inf>-N concentration in the 0-15 cm soil than NR. The NO<inf>3</inf>-N concentration in the 0-15, 15-30 and 30-60 cm soil layers increased (though small) with increasing N rate. The R treatment had 6.7% lower proportion of fine (<0.83 mm diameter) and 8.6% greater proportion of large (>38.0 mm) dry aggregates, and 4.5 mm larger mean weight diameter (MWD) compared to NR treatment. This suggests a lower potential for soil erosion when crop residues are retained. There was no beneficial effect of elimination of tillage on soil aggregation. The amount of N lost as N<inf>2</inf>O was higher from N-fertilized (580 g N ha-1) than from zero-N (155 g N ha-1) plots, and also higher in CT (398 g N ha-1) than NT (340 g N ha-1) in some cases. In conclusion, retaining crop residues along with no-tillage improved some soil properties and may also be better for the environment and the sustainability of high crop production. Nitrogen fertilization improved crop production and some soil quality attributes but also increased the potential for NO<inf>3</inf>-N leaching and N<inf>2</inf>O-N emissions, especially when applied in excess of crop requirements. Crown Copyright © 2007.		
Malhi, S.S.; Lemke, R.L.; Wang, Z.H.; Chhabra, B.S.	2006	Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and	Management practices that simultaneously improve soil properties and yield are crucial to sustain high crop production and minimize detrimental impact on the environment. The objective of this study was to determine the influence of tillage and crop residue management on crop yield, N uptake and C removal in crop, soil organic C and N, inorganic N and aggregation, and nitrous oxide (N<inf>2</inf>O) emissions on a Gray Luvisol (Boralf) soil near Star City, Saskatchewan,	Soil and Tillage Research	10.1016/j.still.2005.09.001

		greenhouse gas emissions	Canada. The 4-year (1998-2001) field experiment was conducted with two tillage systems: no tillage (NT), and conventional tillage (CT); two levels of straw: straw retained (S), and straw removed (NS); and four rates of fertilizer N: 0, 40, 80, and 120 kg N ha-1, except no N to pea phase of the rotation. The plots were seeded to barley (Hordeum vulgare L.) in 1998, pea (Pisum sativum L.) in 1999, wheat (Triticum aestivum L.) in 2000 and canola (Brassica napus L.) in 2001. Tillage and straw treatments generally had no effect on crop yield during the first three years. But in 2001, NT produced 55, 32, and 20% greater canola seed, straw and chaff than CT, respectively, whereas straw retention increased seed and straw yield by 33 and 19% compared to straw removal. Seed, straw and chaff yield of canola increased with N rate up to 40 kg N ha-1, and root mass (0-15 cm depth) with N rate to 80 kg N ha-1. Amount of N uptake and C removed in wheat and canola generally increased with N rate, but tillage and straw management had no consistent effect. After four crop seasons, total organic C (TOC) and N (TN), light fraction organic matter (LFOM), C (LFC), and N (LFN) were generally greater with S than NS treatments. Tillage did not affect TOC and TN in soil, but LFOM, LFC, and LFN were greater or tended to be greater under NT than CT. There was no effect of tillage, straw and N fertilization on NH<inf>4</inf>-N in soil, but CT and S tended to have higher NO<inf>3</inf>-N concentration in 0-15 cm soil than NT and NS, respectively. Concentration of NO<inf>3</inf>-N increased substantially with N rate ≥80 kg ha-1. The NT + S treatment had the lowest proportion (34%) of wind-erodible (<0.83 mm diameter) aggregates and greatest proportion (37%) of larger (>12.7 mm) dry aggregates, compared to highest (50%) and lowest (18%) proportion of corresponding aggregates in CT + NS, indicating less potential for soil erosion when tillage was omitted and crop residues were retained. Amount of N lost as N<inf>2</inf>O was higher from N-fertilized than from zero-N plots, and it was substantially higher from N-applied CT plots than from N-applied NT plots. Retaining crop residues along with no-tillage improved soil properties and may also be better for the environment. © 2005 Elsevier B.V. All rights reserved.		

McConkey, B.; Campbell, C.A.; Zentner, R.P.; Dyck, F.B.; Selles, F.	1996	Long-term tillage effects on spring wheat production on three soil textures in the brown soil zone	The adoption of reduced tillage practices has increased markedly on the Canadian prairies in recent years. Producers in the semiarid Brown Chernozemic soil zone require information on how the intensity of tillage will affect moisture conservation and grain yields in the long term. A 12-yr study was conducted in the Brown soil zone of southwestern Saskatchewan on Swinton silt loam (Orthic Brown), Hatton fine sandy loam (Orthic Brown), and Sceptre heavy clay (Rego Brown) to determine the influence of tillage on the production of hard red spring wheat (Triticum aestivum L.) (on the silt loam and clay) and durum (Triticum turgidum L.) (on the sandy loam). The study was conducted with fallow-wheat (F-W) and continuous wheat (continuous W) rotations. The tillage systems were no-tillage (NT), minimum tillage (MT) and conventional tillage (CT). On the sandy soil with its low water-holding characteristics, tillage system did not affect stored spring soil moisture (SSM), nor grain yields, nor grain N. On the silt loam and clay, there were several instances when NT increased stored moisture in the soil, especially on the clay, but the extra moisture conserved was not always associated with increased grain yields. Generally, when significant increases in stored moisture for F-W were accompanied by below-average growing season precipitation (GSP), an advantage in yield accrued to NT. However, when GSP was above average, CT and MT often had greater yields than NT. We rarely observed yield advantages favouring NT on continuous W on the silt loam or on the clay. Our results suggest that wheat grown under NT on the clay has a higher lower limit of available soil moisture than under CT. Generally, grain N concentration was lower for F-W (NT) on the silt loam and clay. This study has shown that monoculture wheat production in the Brown soil zone was influenced little by tillage system.	Canadian Journal of Plant Science	10.4141/cjps96-127

McConkey, B.; Curtin, D.; Campbell, C.A.; Brandt, S.; Selles, F.	2002	Crop and soil nitrogen status of tilled and no-tillage systems in semiarid regions of Saskatchewan	We examined 1990-1996 crop and soil N data for no-tillage (NT), minimum tillage (MT) and conventional tillage (CT) systems from four long-term tillage studies in semiarid regions of Saskatchewan for evidence that the N status was affected by tillage system. On a silt loam and clay soil in the Brown soil zone, spring what (Triticum aestivum L.) grain yield and protein concentration were lower for NT compared with tilled (CT or MT) systems for a fallow-wheat (F-W) rotation. Grain protein concentration for continuous wheat was also lower for NT than for MT. For a sandy loam soil in the Brown soil zone, durum (Triticum durum L.) grain protein concentration was similar for MT and NT for both continuous W and F-W, but NT had higher grain yield than MT ($P < 0.05$ for F-W only). For a loam soil in the Dark Brown soil zone, wheat grain yield for NT was increased by about 7% for fallow-oilseed-wheat (F-O-W) and wheat-oilseed-wheat (W-O-W) rotations. The higher grain yields for NT reduced grain protein concentration by dilution effect as indicated by similar grain N yield. However, at this site, about 23 kg ha-1 more fertiliser N was required for NT than for CT. Elimination of tillage increased total organic N in the upper 7.5 cm of soil and N in surface residues. Our results suggest that a contributing factor to decreased availability of soil N in medium- and fine-textured soils under NT was a slower rate of net N mineralisation from organic matter. Soil nitrates to 2.4 m depth did not indicate that nitrate leaching was affected by tillage system. Current fertiliser N recommendations developed for tilled systems may be inadequate for optimum production of wheat with acceptable grain protein under NT is semiarid regions of Saskatchewan.	Canadian Journal of Soil Science	10.4141/S01-036

Mooleki, S.P.; Schoenau, J.; Charles, J.L.; Wen, G.	2004	Effect of rate, frequency and incorporation of feedlot cattle manure on soil nitrogen availability, crop performance and nitrogen use efficiency in east-central Saskatchewan	A study was initiated in 1996 in the Black Soil zone in east-central Saskatchewan to examine soil and crop response to application of feedlot cattle manure at different application rates, frequencies and incorporation timing in a sandy loam and loam soil. Three rates of feedlot cattle manure (approx. 100, 200 and 400 kg total N ha-1) were applied annually and under reduced frequency application regimes. Canola (Brassica napus, L.), spring wheat (Triticum aestivum, L.), hull less barley (Hordeum vulgare, L.) and canola were seeded in spring of 1997, 1998, 1999 and 2000, respectively. Pre-seeding available N (0-60 cm) increased with application rates. Annual application resulted in a linear increase in grain yield with application rates but had no effect on grain N concentration. Cumulative N use efficiency was low (7-10%) with no significant difference among treatments. Single application showed significant residual fertility benefit in the second year but not in the third year except at the high rate. Incorporation timing of feedlot cattle manure had no impact on soil or crop performance. Low availability of N in feedlot cattle manure over the short-term suggests the need for high application rates or addition of supplemental N fertilizer in order to meet crop N requirements.	Canadian Journal of Soil Science	10.4141/S02-045
Newton, A.C.; Guy, D.C.; Nadziak, J.; Gacek, E.S.	2002	The effect of inoculum pressure, germplasm selection and environment on spring barley cultivar mixtures efficacy	A range of mixtures including one set made from cultivars grown in the UK and one from cultivars grown in Poland, were included, along with their component cultivars, in nine trials at Scottish Crop Research Institute, Dundee, UK or at the Experimental Plant Breeding Station of the IHAR, Baków near Kluczbork, Poland, over five seasons. The effects of inoculum pressure, plot size, fertiliser level and germplasm on mixture efficacy were investigated. In the four trials where inoculum pressure was controlled, mixtures reduced infection more at lower inoculum pressures, but this did not translate into yield benefit. Smaller plots increased mildew in monocultures but not mixtures. Fertiliser levels increased mildew levels but did not affect mixture efficacy. There were large differences between both Polish and UK germplasm, and between Polish and UK trial sites, but the performance of the mixtures compared with their respective monoculture components was similar within both germplasm groups and trial sites. Mixtures reduced lodging	Euphytica	10.1023/A:1016052121581

			and affected plant height and heading date. The advantages of mixtures for improving yield, reducing fungicide applications and improving agronomic characteristics was demonstrated and there seems to be great potential for their further improvement and exploitation.		
Nyiraneza, J.; Cambouris, A.N.; Ziadi, N.; Tremblay, N.; Nolin, M.C.	2012	Spring wheat yield and quality related to soil texture and nitrogen fertilisation	Efficient N fertilisation is crucial for economic wheat (Triticum aestivum L.) production and is of great agronomical and environmental significance. A study was conducted at 12 site-years in eastern Canada to evaluate the effect of soil surface textural groups, N rate (0-200 kg N ha-1) and application timing on grain yield (GY), N uptake, nitrogen uptake efficiency (NUE), grain protein content (GPC), test weight, and thousand kernel weight (TKW). Chlorophyll meter readings (CMR) were taken at tillering and at flowering to assess in-season wheat N nutrition. Fertilisation and soil textural group effects were significant on all measured parameters, and their interaction was significant on GPC, TKW, test weight, and CMR. Total N uptake and GPC ranged from 39 to 96 kg N ha-1 and from 13 to 18 g kg-1, respectively, and total N uptake increased proportionally to N rates. Applying N levels >120 kg N ha-1 did not increase total yield, test weight, TKW, or CMR values. The variation in GY, N uptake, and GPC explained by the relative CMR taken at flowering was 87, 88, and 73%, respectively. This study demonstrates that in-season wheat N nutrition can be monitored by CMR and that surface soil texture is an important parameter that influences wheat N response and wheat quality parameters. Applying half of the recommended rate (120 kg ha-1) at planting and the rest at tillering resulted in a high total yield, high grain N uptake, and the highest GPC price premium. © 2012 by the American Society of Agronomy. 5585 Guilford Road, Madison, WI 53711. All rights reserved.	Agronomy Journal	10.2134/agronj2011.0342

O'Donovan, J.T.; Turkington, T.K.; Edney, M.J.; Juskiw, P.E.; McKenzie, R.H.; Harker, K.N.; Clayton, G.W.; Lafond, G.P.; Grant, C.A.; Brandt, S.; Johnson, E.N.; May, W.E.; Smith, E.G.	2012	Effect of seeding date and seeding rate on malting barley production in western Canada	Barley (Hordeum vulgare L.) growers in western Canada often have difficulty achieving malting grade. This is usually due to unfavourable climatic conditions, but sub-optimal agronomic practices may also be a factor. Field experiments were conducted in 2006, 2007 and 2008 at eight locations in western Canada (24 site-years) to evaluate the effects of seeding date (relatively early and late) and seeding rate (100, 200, 300, 400 and 500 seeds m -2) on AC Metcalfe barley yield and malt quality parameters. Delayed seeding often resulted in negative effects including increased protein concentration, decreased kernel plumpness and yield. However, at 6 site-years, higher yields occurred at the later seeding date. 300 seeds m -2 was usually optimal; maintained or improved yield, decreased protein concentration, increased kernel uniformity and time to seed maturity, and decreased tillering. In most cases, seeding at more than 300 seeds m -2 did not result in an improved outcome, and there was a risk of reduced yield and kernel plumpness at rates above this level. A multivariate analysis indicated that relatively low barley plant densities were associated primarily with northern locations with low soil pH.	Canadian Journal of Plant Science	10.4141/CJPS2011-130
Olesen, J.E.; Askegaard, M.; Rasmussen, I.A.	2009	Winter cereal yields as affected by animal manure and green manure in organic arable farming	The effect of nitrogen (N) supply through animal and green manures on grain yield of winter wheat and winter rye was investigated from 1997 to 2004 in an organic farming crop rotation experiment in Denmark on three different soil types varying from coarse sand to sandy loam. Two experimental factors were included in the experiment in a factorial design: (1) catch crop (with and without), and (2) manure (with and without). The four-course crop rotation was spring barley undersown with grass/clover - grass/clover - winter wheat or wheat rye - pulse crop. All cuttings of the grass-clover were left on the soil as mulch. Animal manure was applied as slurry to the cereal crops in the rotation in rates corresponding to 40% of the N demand of the cereal crops. Application of 50 kg NH<inf>4</inf>-N ha-1 in manure increased average wheat grain yield by 0.4-0.9 Mg DM ha-1, whereas the use of catch crops did not significantly affect yield. The use of catch crops interacts with other management factors, including row spacing and weed control, and this may have contributed to the negligible effects of catch crops. There was	European Journal of Agronomy	10.1016/j.eja.2008.08.002

			considerable variation in the amount of N (100-600 kg N ha-1 year-1) accumulated in the mulched grass-clover cuttings prior to ploughing and sowing of the winter wheat. This was reflected in grain yield and grain N uptake. Manure application to the cereals in the rotation reduced N accumulation in grass-clover at two of the locations, and this was estimated to have reduced grain yields by 0.1-0.2 Mg DM ha-1 depending on site. Model estimations showed that the average yield reduction from weeds varied from 0.1 to 0.2 Mg DM ha-1. The weed infestation was larger in the manure treatments, and this was estimated to have reduced the yield benefit of manure application by up to 0.1 Mg DM ha-1. Adjusting for these model-estimated side-effects resulted in wheat grain yields gains from manure application of 0.7-1.1 Mg DM ha-1. The apparent recovery efficiency of N in grains (N use efficiency, NUE) from NH<inf>4</inf>-N in applied manure varied from 23% to 44%. The NUE in the winter cereals of N accumulated in grass-clover cuttings varied from 14% to 39% with the lowest value on the coarse sandy soil, most likely due to high rates of N leaching at this location. Both NUE and grain yield benefit in the winter cereals declined with increasing amounts of N accumulated in the grass-clover cuttings. The model-estimated benefit of increasing N input in grass-clover from 100 to 500 kg N ha-1 varied from 0.8 to 2.0 Mg DM ha-1 between locations. This is a considerably smaller yield increase than obtained for manure application, and it suggests that the productivity in this system may be improved by removing the cuttings and applying the material to the cereals in the rotation, possibly after digestion in a biogas reactor. Cereal grain protein content was increased more by the N in the grass-clover than from manure application, probably due to different timing of N availability. Green-manure crops or manures with a relatively wide C:N ratio may therefore be critical for ensuring sufficiently high protein contents in high yielding winter wheat for bread making. © 2008 Elsevier B.V. All rights reserved.		

Olesen, J.E.; Hansen, E.M.; Askegaard, M.; Rasmussen, I.A.	2007	The value of catch crops and organic manures for spring barley in organic arable farming	The effect of nitrogen (N) supply and weeds on grain yield of spring barley was investigated from 1997 to 2004 in an organic farming crop rotation experiment in Denmark on three different soil types varying from coarse sand to sandy loam. Two experimental factors were included in the experiment in a factorial design: (1) catch crop (with and without), and (2) manure (with and without). The crop rotation included grass-clover as a green manure crop. Animal manure was applied as slurry in rates corresponding to 40% of the N demand of the cereal crops. Application of 50 kg NH<inf>4</inf>-N ha-1 in manure (slurry) increased average barley grain DM yield by 1.0-1.3 Mg DM ha-1, whereas the use of catch crops (primarily perennial ryegrass) increased grain DM yield by 0.2-0.4 Mg DM ha-1 with the smallest effect on the loamy sand and sandy loam soils and the greatest effect on the coarse sandy soil. Model estimations showed that the average yield reduction from weeds varied from 0.2 to 0.4 Mg DM ha-1 depending on weed species and density. The yield effects of N supply were more predictable and less variable than the effects of weed infestation. The infestation level of leaf diseases was low and not a significant source of yield variation. The apparent recovery efficiency of N in grains (N use efficiency, NUE) from NH<inf>4</inf>-N in applied manure varied from 29 to 38%. The NUE of above-ground N in catch crops sampled in November prior to the spring barley varied from 16 to 52% with the largest value on the coarse sandy soil and the smallest value on the sandy loam soil. A comparison of grain yield levels obtained at the different locations with changes in soil organic matter indicated a NUE of 21-26% for soil N mineralisation, which is smaller than that for the mineral N applied in manure. However, this estimate is uncertain, and further studies are needed to quantify differences in NUE from various sources of N. The proportion of perennial weeds in total biomass increased during the experiment, particularly in treatments without manure application. The results show that manure application is a key factor in maintaining good crop yields in arable organic farming on sandy soils, and in securing crops that are sufficiently competitive against perennial weeds. © 2006 Elsevier B.V. All rights reserved.	Field Crops Research	10.1016/j.fcr.2006.07.001

Paire, L.; McCabe, C.; McCabe, T.	2025	Multi-year organic field evaluation of a diverse panel of spring naked barley accessions for feed, food, and malting use	The study objectives were to evaluate a diverse panel of 247 spring naked barley varieties under Irish organic conditions and identify the best-performing lines for multi-use purposes. A trial was conducted on an Irish organic certified field over three years (2019–2021), following a type II modified augmented design (MAD2). The genotypes were evaluated on phenology, agronomy, diseases, threshability, and grain quality. Genotypic effects were significant with heritability above 60% showing good selection opportunities. However, significant genotype-by-year interactions highlighted the importance of trait stability in the selection process. Best performing lines were identified with the Multi-trait Genotype Ideotype Distance Index (MGIDI) using two different ideotypes: MGIDI1 selected 23 lines and was focused on grain quality with yield, lodging resistance, TKW, chemical grain quality and threshability, while MGIDI2 selected 16 lines and comprised additional yield-related traits including early vigour, plant height, green leaf area, diseases infection, phenological characteristics and grain plumpness. The characterisation of selection panels highlighted that MGIDI is a valuable tool for increasing genetic gain while preserving genetic diversity. Results showed that yield-related traits influenced yield formation differently across variable climate conditions, and including plant characteristics providing climate resilience may favour long-term genetic gain. Six lines, selected with either MGIDI2 or both MGIDI1 and MGIDI2, exhibited good overall performance across key traits: HB16338, CDC Clear, Purple Prince, 10WA-127.5, Lawina (Myrtle-Creek), and DH140285. Those can be used as parents in future breeding cycles, while other selected lines remain interesting material for crossbreeding. © The Author(s), under exclusive licence to Springer Nature B.V. 2024.	Euphytica	10.1007/s10681-024-03447-7

Riley, H.C.F.	1998	Soil mineral-N and N-fertilizer requirements of spring cereals in two long-term tillage trials on loam soil in southeast Norway	Much uncertainty exists among growers concerning the need to adjust N-fertilizer application to cereals when reduced tillage is adopted. Studies in long-term trials are required to give an adequate answer to this question, which is of both economic and environmental interest. N-fertilizer requirements of spring cereals and of soil mineral nitrogen contents at different times of the year were measured over the period 1991-1996 in two long-term tillage trials established in 1980 at Kise (60°46'N, 10°49'E) on morainic loam soil. Tillage treatments comprised conventional tillage with autumn ploughing and reduced tillage without ploughing and with harrowing in spring kept to the minimum necessary for seeding. Four levels of N-fertilizer (0, 60, 90 and 120 kg N/ha) were compared in 1991-1995 in barley (Hordeum vulgare L.) and wheat (Triticum aestivum L.), and their residual effect was measured in 1996. Levels of soil mineral nitrogen before fertilization in spring were on an average 8% lower with reduced tillage than with conventional tillage. Plant development was delayed with reduced tillage, but this was compensated for later in the season. A two-year incubation study under covered plots in the field did not reveal any effect of tillage on net nitrogen mineralisation. There was a tendency to higher straw yield with reduced tillage, but no overall effect on grain yield. Responses to N-fertilizer were almost identical with both the tillage systems, and yields increased up to the highest level of application. Crop nitrogen contents were monitored, but only minor differences were found between tillage systems in total uptakes and apparent N-fertilizer recoveries. On the basis of these results, it is concluded that long-term reduced tillage does not affect the N-fertilizer requirements of spring cereals on loam soils under cool climatic conditions.	Soil and Tillage Research	10.1016/S0167-1987(98)00165-2

Soon, Y.K.; Clayton, G.W.	2002	Eight years of crop rotation and tillage effects on crop production and N fertilizer use	Although tillage systems and crop rotations can affect crop production and uptake of nutrients, their long-term effects, particularly their interactions, are not well-documented. Therefore, we measured the N, P, and K contents and yields of crops through two rotation cycles, especially wheat (Triticum aestivum L.), of four crop rotations managed under conventional tillage (CT) and no-tillage (NT) systems. The study was conducted 1993 through 2000 on a sandy loam soil in northwestern Alberta, Canada. The four-course crop rotations were: (i) field pea (Pisum sativum L.)-wheat-canola (Brassica rapa L.)-wheat; (ii) red clover (Trifolium pratense L.) green manure-wheat-canola-wheat; (iii) fallow-wheat-canola-wheat, and (iv) continuous wheat (CW). The crops were fertilized using regional recommendations based on soil test results. Previous crop effect on wheat yield was in the order: field pea = red clover green manure > fallow > canola > wheat (CW); it had little influence on N, P or K content in wheat grain or straw. There was no interaction of tillage with crop rotation on wheat production or nutrient content. Tillage treatments affected neither production of other rotation crops nor their nutrient concentrations. During the second rotation cycle, N fertilizer requirement decreased, and wheat yield was 22% higher, under NT as compared to CT. This study showed that (i) field pea is an attractive replacement for red clover green manure; and (ii) recommendations for N from soil test results should factor in the type of tillage system used.	Canadian Journal of Soil Science	10.4141/S01-047

Turkington, T.K.; O'Donovan, J.T.; Edney, M.J.; Juskiw, P.E.; McKenzie, R.H.; Harker, K.N.; Clayton, G.W.; Xi, K.; Lafond, G.P.; Irvine, R.B.; Brandt, S.; Johnson, E.N.; May, W.E.; Smith, E.G.	2012	Effect of crop residue, nitrogen rate and fungicide application on malting barley productivity, quality, and foliar disease severity	The productivity and quality of the malting barley cultivar AC Metcalfe and leaf disease severity were evaluated under three residue types [barley (Hordeum vulgare L.), canola (Brassica napus L.), field pea (Pisum sativum L.)], two nitrogen (N) fertiliser rates (50 or 100% of soil test recommendation for N), and two fungicide treatments (no fungicide or fungicide applied) at seven sites across western Canada from 2006 to 2009. Residue type had a significant effect on leaf disease severity, which was increased when barley was the previous crop compared with canola and field peas. In general, emergence, head counts, grain yield, kernel weight, test weight, kernel plumpness were lowest for barley grown on barley residue compared with canola and field pea residue. Fungicide application reduced leaf disease severity and increased yield, kernel weight, test weight, and kernel plumpness, while decreasing dockage and thins. However, the magnitude of the impact of fungicide on one or more of these parameters was lower compared with planting barley on field pea or canola residue. Overall, increasing the N rate from 50 to 100% had no effect on leaf disease levels and only increased yields slightly compared with not planting barley on barley residue. However, the 100% rate of N did significantly increase grain protein levels. In contrast, planting barley on field pea residue did not result in a consistent increase in grain protein.	Canadian Journal of Plant Science	10.4141/CJPS2011-216

Wani, S.P.; McGill, W.B.; Tewari, J.P.	1991	Mycorrhizal and common root-rot infection, and nutrient accumulation in barley grown on breton loam using N from biological fixation or fertilizer	This paper presents soil biological data from a study on the functioning of three soil-plant systems on a Gray Luvisol in Cryoboreal Subhumid central Alberta. The systems were (1) an agroecological 8-year rotation, (2) a continuous grain system, both established in 1981, and (3) a classical Breton 5-year rotation established in 1930. The objectives were to (1) determine whether changes in vesicular-arbuscular mycorrhizae (VAM) populations occurred in soil under these cropping systems, (2) discover whether these cropping systems and/or VAM infection influenced the incidence of common root rot (Bipolaris sorokiniana), and (3) use nutrient translocation indices to test the hypothesis that soil quality influences non-specific physiological conditions in barley (Hordeum vulgare L.). VAM fungal propagules in soil samples and VAM infection under controlled conditions were significantly affected by the cropping system. VAM infection accounted for more than 85% of the variability in grain yield, plant biomass yield, and plant uptake of K, S, Ca, Fe, and Zn under controlled conditions. Backward-elimination regression analyses showed that under these conditions of high available P, plant P uptake was governed by the quantity of extractable P in the soil (r2=0.82); the VAM infection contributed practically nothing when combined with available P (R2=0.84). Neither VAM infection nor the cropping system were related to the B. sorokiniana infection in the barley. The growth of B. sorokiniana was equal, and its sporulation superior, when grown on residues of the non-host fababean (Vicia faba L.), compared with growth on residues of barley. Higher translocation of plant nutrients to the grain in the agroecological compared with the continuous grain treatments suggested that VAM and/or the soil history affected plant physiology, possible through hormonal effects. Superior barley yields in the agroecological compared with the continuous grain treatments were partly due to increased VAM colonization, greater nutrient accumulation and translocation to the grain, but not to a reduced disease incidence. These results demonstrate the benefits of a holistic systems approach while studying biological interactions involving plants and groups of soil microorganisms. © 1991 Springer-Verlag.	Biology and Fertility of Soils	10.1007/BF00369387

Wen, G.; Schoenau, J.; Charles, J.L.; Inanaga, S.	2003	Efficiency parameters of nitrogen in hog and cattle manure in the second year following application	The efficiency of nitrogen (N) derived from different manures in the years following application must be determined to optimize use of N and reduce impact on the environment. Five N efficiency parameters that were originally developed for commercial inorganic N fertilizers were selected to measure the manure N efficiency in the second year following application of liquid hog and solid cattle manure in semiarid east-central Saskatchewan, Canada. The manures were applied at two sites (Dixon and Burr) at four rates covering a range from zero to 912 kg N ha-1 in 1997. A canola (Brassica napus L.) crop was grown in 1997 followed by a spring wheat (Triticum aestivum L.) in 1998 without fertilization. Tested by the wheat, N utilization efficiency (NUE) was similar between the two manures at either site, but it was higher at Dixon site, where the soil properties were better, than at the Burr site (P < 0.07) with cattle manure. Nitrogen physiological efficiency (NPE) was not affected by either manure source or soil. At the Burr site, N agronomic efficiency (NAE) and N recovery rate (NRR) were all higher with the hog than with the cattle manure (P < 0.08 and P < 0.07, respectively), but N harvest index (NHI) was lower with the hog than with the cattle manure (P < 0.04). The similar trends of the NAE, NRR, and NHI between the hog and cattle manure were also found at the Dixon site. However, the differences in NRR between the hog and cattle manure in the second year was rather small in contrast to the large differences in the year of application. Despite that the wheat crop utilized residual hog and cattle manure N equally efficient in producing grain yield, a higher grain N concentration and a higher NHI with the cattle than with the hog manure revealed different N supply dynamics between the two. Possibly due to the low proportion of ammonium (NH<inf>3</inf>)-N in the total N and the high C:N ratio in the cattle manure, mineralization of cattle manure N provided more available N in the later stage of wheat growth than did the hog manure. The N efficiency parameters were useful tools in understanding the impact of residual manure N on wheat production on the Canadian prairies.	Journal of Plant Nutrition and Soil Science	10.1002/jpln.200321135

Yan, Z.; Xu, Y.; Chu, J.; Guillaume, T.; Bragazza, L.; Li, H.; Shen, Y.; Yang, Y.; Zeng, Z.; Zang, H.	2025	Long-term diversified cropping promotes wheat yield and sustainability across contrasting climates: Evidence from China and Switzerland	Context: Crop diversification is extensively advocated to buffer against climate variability and extreme events to increase crop yields and agroecosystem services. Objective: This study aimed to investigate the long-term implications of diversified cropping on wheat yield and soil quality in contrasting climate regions. Methods: A five-decade field experiment in a temperate sub-maritime climate (Nyon, Switzerland) and a two-decade field experiment in a temperate continental climate (Luancheng, China) were carried out to investigate the effects of diversified cropping on wheat yield, yield stability and sustainability, and soil quality. Results: The long-term diversified cropping increased wheat yield by 16.2% in the sub-maritime climate and 15.0% in the continental climate. In the sub-maritime climate, diversified cropping increased mean wheat yield stability and sustainability by 5.8% and 17.3%, respectively. In the continental climate, diversified cropping increased wheat yield stability by 3.7% and sustainability by 12.3%. Dynamic stability analysis confirmed that wheat yield under diversified cropping was higher in high-yielding years across climates. However, soil organic carbon (C) and soil quality showed minimal variation with long-term cropping systems and tillage practices. Conclusions: Diversified cropping serves as a promising strategy for enhancing wheat yield stability and sustainability while maintaining soil quality. Implications: This research fills a critical gap in understanding how diversified cropping systems perform under real-world conditions over decades under climate change, offering land managers actionable data for balancing crop productivity with soil quality in sustainable agricultural practices. © 2025 Elsevier B.V.	Field Crops Research	10.1016/j.fcr.2025.109764

Appendix 3 – Grey literature - Selected reports

Authors	Year	Title	Source	Link	Document	Open access
Brown, I. and Matthews, R.	2012	Summary of research relevant to adaptation to climate change in the agricultural sector in Scotland	Climate X Change	Current and Future Windstorms in Scotland (Accessed on 15/12/2025)	Report	Open access
Burnett, F.	2024	AHDB	Annual Project Report (harvest 2024) On-farm trials at Strategic Cereal Farm Scotland	Strategic Cereal Farm Scotland annual report (harvest 2024).pdf (Accessed on 15/12/2025)	Report	Open access
Cooper, J., Stockdale, E. and Clarke, B.	2024	D2: A summary of key knowledge gaps, research needs and ways to address them	Organic Research Centre	https://www.organicresearchcentre.com/wp-content/uploads/2023/11/D2-Final-report-on-REA-on-Regen-Ag-v11.pdf (Accessed on 15/12/2025)	Report	Open access
Cunningham-Eurish, I., Wentworth, J.	2025	Regenerative Agriculture	UK Parliament Post	Regenerative agriculture (Accessed on 15/12/2025)	Report	Open access
Fiennes, Jake	2025	Regenerative Agriculture in the UK: An ecological perspective	British Ecological Society	https://www.britishecologicalsociety.org/wp-content/uploads/2025/04/BES_Regenerative-agriculture-report_2025.pdf (Accessed on 15/12/2025)	Report	Open access
Jenkins, T., Randall, N.	2025	Research Review 101a Updating cover crop guidance (Part A): destruction methods		https://projectblue.blob.core.windows.net/media/Default/Research%20Papers/Cereals%20and%20Oilseed/2025/RR101a%20final%20project%20report.pdf (Accessed on 15/12/2025)	Report	Open access

Nabuurs, G. and Mrabet, R.	2022	Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)	IPCC	Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU) (Accessed on 15/12/2025)	Report	Open access
Spink, J., Hennessy, M., Hackett, R., Wall., D.	2025	An environmental and economic assessment on the impact of possible reductions in the maximum chemical nitrogen allowances for main arable crops.	Teagasc	An-environmental-and-economic-assessment-on-the-impact-of-possible-reductions-in-the-maximum-chemical-nitrogen-allowances-for-main-arable-crops.pdf (Accessed on 15/12/2025)	Report	Open access
Thoman, R., Bhogal, A., Kendle, S. and Bailey, G.	2024	NiCCs – Nitrogen release from Cover Crops, 2021-2023 FINAL	Affinity Water	NiCCs-final-report-_January-2024-FINAL.pdf (Accessed on 15/12/2025)	Report	Open access



Aberdeen

The James Hutton Institute
Craigiebuckler
Aberdeen AB15 8QH
Scotland
UK

Farms

Balruddery Research Farm
Invergowrie
Dundee DD2 5LJ

Dundee

The James Hutton Institute
Invergowrie
Dundee DD2 5DA
Scotland
UK

Glensaugh Research Farm
Laurencekirk
Aberdeenshire AB30 1HB

Contact

Tel: +44 (0) 344 928 5428
Fax: +44 (0) 344 928 5429

info@hutton.ac.uk