Benchmarking greenhouse gas emissions for the UK arable and horticultural sector

Supporting the journey to net zero...

SUMMARY REPORT 2022

AHDB CHAP CROP HEALTH & PROTECTION *with thanks to* ADAS

UK agriculture's net zero opportunity

Executive Summary

Reaching net zero in the arable and horticultural sector may not seem easy, but is achievable. Farming's unique ability to capture carbon from the atmosphere underpins the opportunity to deliver net zero for farming, as well as the potential to support other UK sectors to reach net zero, provided that a robust and viable value can be placed on this carbon.

Without baseline benchmarking, we cannot define our starting point and it becomes difficult to achieve the rate of change necessary, or make comparisons with international competitors; that is why this report was commissioned.

Driving reductions in the climate impact of production can be achieved through reducing emissions from the manufacture and use of nitrogen fertiliser, fuel, and energy use associated with storing produce, in particular. These positive actions will reduce emissions per hectare and absolute emissions, while maintaining or increasing production.

Residual emissions can be balanced by enhancing carbon capture on farm (both nature-based and engineered carbon removals), and it is also important to protect carbon already stored in soils, grassland and woodlands.

All farmers can continue to make improvements to their resource efficiency to reduce emissions, while in the medium-term new technologies to help decarbonise some of the embedded emissions in raw materials brought onto farm will help.

Carbon sequestration in vegetation and soils offers a valuable tool for achieving net zero, although uncertainties make it crucial to better understand permanence or dynamic stability (long-term storage), when saturation will occur (for example, there is only a finite amount of carbon that can be stored in soils), and the impact of actions on leakage (moving carbon from one location to another).

Longer term, optimising land use for production and "carbon farming" (both nature-based and engineered) may offer greater opportunities for farmers to participate in carbon removals, but funding through public or private mechanisms will be vital.

Innovation within the agricultural sector is key to supporting farmers and the wider industry to be ambitious and to achieve this goal, which will also deliver broader sustainability co-benefits.

In working towards net zero, farmers could save themselves resources and money, and also boost their farm's resilience to extreme weather. By working in harmony with other food-system interventions, namely cutting food waste and responding to shifts in dietary preferences, the wider industry can maximise its success.

This document summarises a report commissioned by the Agriculture and Horticulture Development Board (AHDB) and Crop Health and Protection (CHAP), which further explores this important topic.

“Farming and wider land management are fundamental to achieving a net zero economy and stabilising global temperatures. This report provides the baseline and knowledge-base to support every farmer to make ambitious changes, and every innovator to develop ambitious solutions, to deliver a sustainable and resilient future for UK agriculture. The sooner we innovate and transition, the greater the benefits will be, and the greater the role UK businesses will have in leading the world’s transformation.”

Dr Harry Langford,
Innovation Lead, CHAP

Dr Jonathan Foot,
Head of Environment, AHDB

“UK farming is facing a once in a generation shift towards a future where levy payers will need to manage sustainability and economic outcomes within their business, whilst trying to balance the competing demands for safe, secure and affordable food for all. This report takes the first steps in ensuring the industry has an independent and trusted baseline for the most important greenhouse gas emission sources, showing how we compare against our international peers and identifying where we have gaps in our knowledge to support future research needs. The report also identifies some practical solutions that can help the industry to increase carbon removals and to reduce emissions as part of the continual journey towards a more resilient business in an increasingly uncertain world.”

Introduction

There is an opportunity for agriculture to play a fundamental role in ensuring that the UK reaches net zero emissions.

What this review highlights

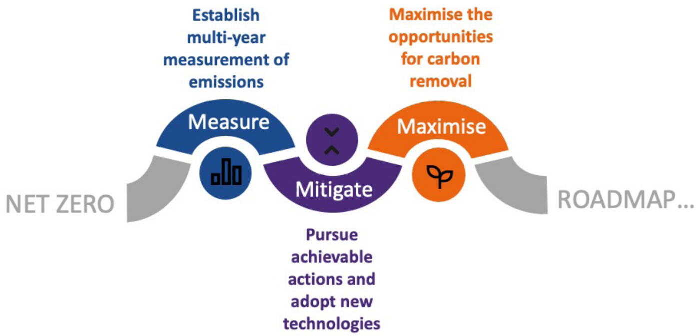
- Benchmark GHG emissions for important UK arable and horticultural crops
- Identifies the most important emission sources for each crop
- Opportunities for reducing emissions on arable and horticultural farms (i.e. the hotspots)
- Opportunities for increasing carbon removals
- A brief overview of the new technologies available to mitigate emissions in cropping systems

Whilst agriculture is a significant contributor to greenhouse gas (GHG) emissions in the UK and globally, farmers also manage some of the largest stores of GHGs on earth (vegetation and soils), which offers a unique potential to mitigate climate change.

The UK government's 2019 Greenhouse Gas Emissions report estimated the sector was directly responsible for around 10% of UK emissions. To address this, in 2019 the NFU set an ambition for agriculture in England and Wales to reach net zero by 2040 – 10 years ahead of the UK government's 2050 net zero target.

Meeting those targets will require us to continue to transform current farm practices and to develop new technologies.

Critically, the arable and horticultural sector needs to better understand the full extent of emissions generated by growing crops, to enable identification of hotspots and opportunities to reduce them.



Any remaining emissions that cannot be eliminated from the production system will need to be balanced through carbon removals.

There is also a potential opportunity to go further – for a limited number of farms to become 'carbon positive' i.e. a source of 'negative emissions' whereby carbon sequestration outweighs greenhouse gases emitted. Indeed, given the current uncertainty around monitoring, additionality and permanence of certain carbon removals (e.g. in soils) it may be desirable for some farms to aim for such 'headroom' in emissions accounting.

The aim of this review is to provide benchmarks of emissions from UK cropping systems from available evidence, to place them in a global context where data is available, and to identify the most important emission sources. The review also highlights opportunities to reduce emissions at source and mitigate any remaining emissions through increasing carbon removals.

Together this information is used to set out achievable actions and goals for a UK cropping sector road map to net zero.

Understanding the review

The report reviews the existing greenhouse gas emission evidence base of assessments completed across arable and horticultural crops grown in the UK, as well as some international comparators. The evidence base has been produced by different authors, using a range of different tools and methods over several years. For some crops the evidence base is more limited, because they have been the subject of fewer good quality studies.

Where there have been assessments by the same author using a consistent approach, it is possible to compare between crops, e.g. those conforming to the 2011 British Standards Institution's PAS2050 product carbon footprinting methodology, or those using a consistent life-cycle analysis approach, such as those for the Global Feed LCA Institute (GFLI).

The data are presented as a series of emission intensities, showing the minimum and maximum values for a crop in the literature and highlighting any differences in approach and methodology that may impact those figures.

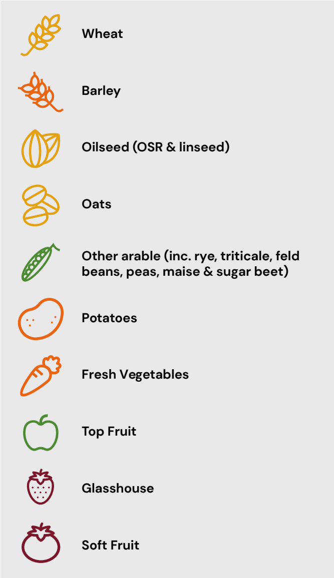
Given that methodologies and emissions factors do change (e.g. the global warming potential of nitrous oxide was reduced from 298 to 265 in 2019, the embedded emissions from fertiliser manufacture in Europe have fallen in the past 10 years, and life cycle analysis (LCA) typically includes more emissions within its scope), some caution has to be applied when making comparisons.

Therefore, an assessment was made of the robustness of the data, with 9 of the 14 data sets evaluated as high quality. More recent figures calculated by a transparent method can be considered the most robust, but the older figures, despite some of the issues outlined above, remain relevant.

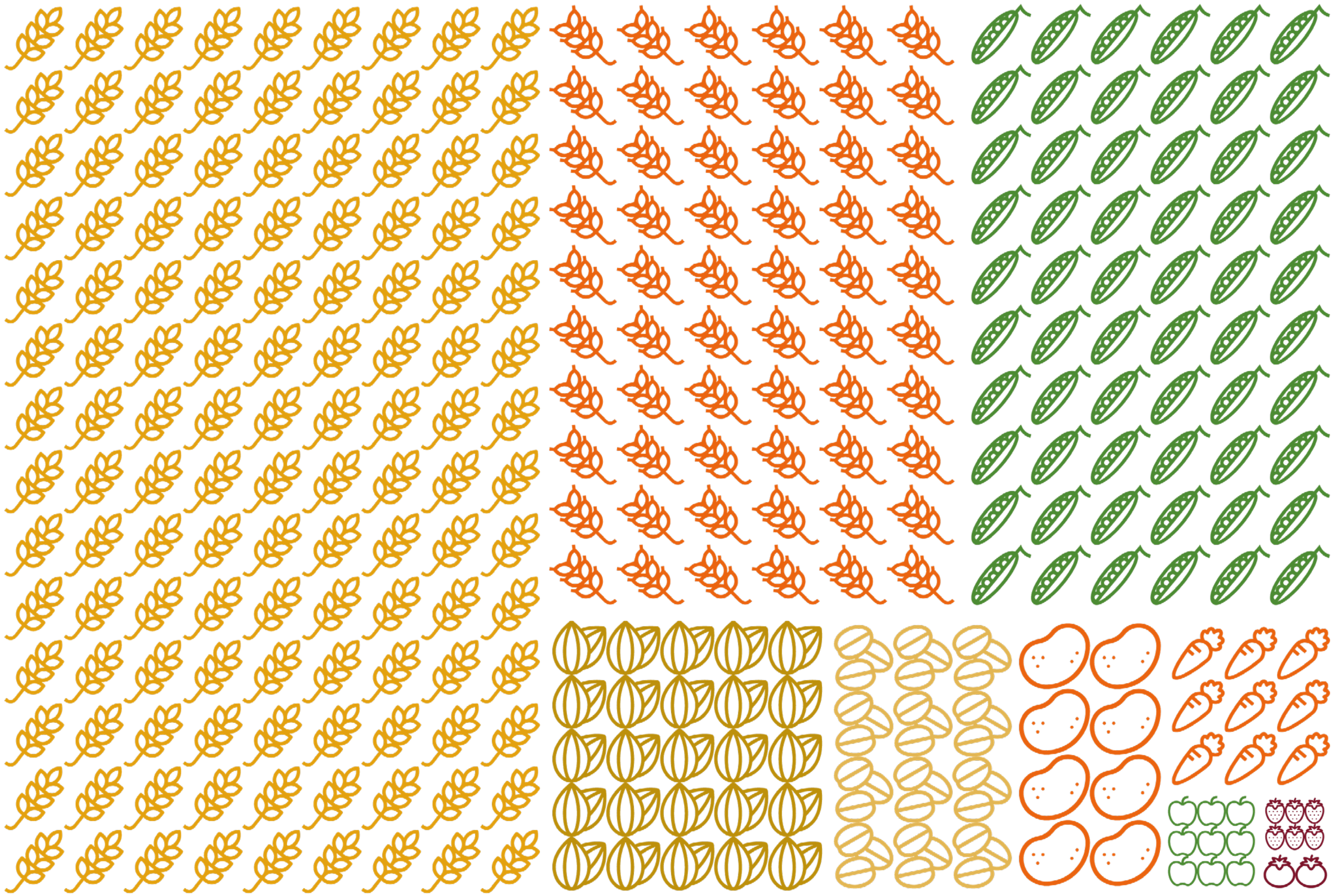
Which crops are included?

Of the six million hectares of croppable land within the UK, nearly three quarters is utilised on an annual basis, of which approximately 70% is utilised for cereal production, with the remainder being split between oilseeds, potatoes and horticultural crops.

This review sets benchmark GHG emissions for the most important UK crops, relating those benchmark figures to the range of literature values available for each crop and comparing them to representative European and global data.



*Proportional representation of the typical UK land use for crop production.



Findings

Snapshot

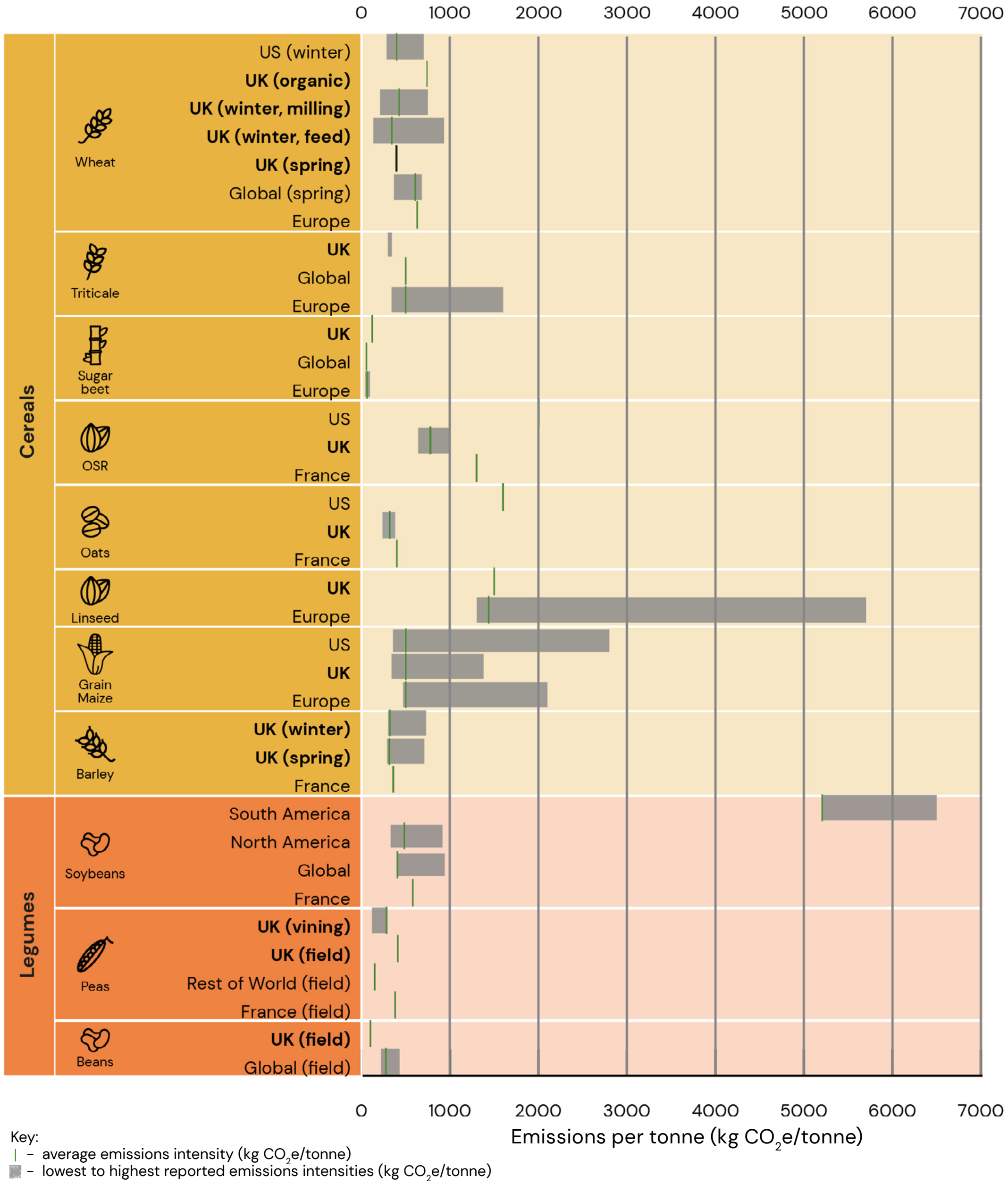
Greenhouse gas emissions from arable crops

The arable cropping sector has the most publicly available primary data from the greatest number of individual farms, allowing us to define benchmarks with high confidence.

Emissions intensities of between 310-470kg CO_2e/t are characteristic of the combinable grain crops, with oilseeds being typically higher, due principally to their greater inputs when normalised for yield, and legumes being typically lower, due principally to their ability to fix nitrogen.

Where the average emission intensity has a narrow range of emissions, this indicates that there were fewer reliable studies upon which to develop an emissions baseline. These are areas where more research is required and readers should acknowledge this limitation.

Emissions per tonne arable crops



Emissions per tonne UK arable crops

Crop type	Benchmark UK emissions intensity (kg CO_2e/tonne)	Lowest reported UK emissions intensity (kg CO_2e/tonne)	Highest reported UK emissions intensity (kg CO_2e/tonne)	Degree of confidence in Benchmark*
Winter wheat (milling)	420	210	750	Green
Winter wheat (feed)	340	130	930	Green
Winter barley	340	300	730	Green
Spring barley	320	290	710	Green
Oats	310	240	380	Green
Triticale	320	300	340	Green
Oilseed rape	740	640	1000	Green
Linseed	1500	–	–	Amber
Grain maize	470	340	1380	Green
Sugar beet	120	–	–	Green
Peas (vining)	290	120	294	Amber
Peas (field)	410	–	–	Green
Beans (field)	100	–	–	Green

Data for this snapshot is from a range of sources: Williams et al. (2006), Audsley et al. (2009), Wiltshire et al. (2009), Gan et al. (2014), Sylvester-Bradley et al. (2015), Clune et al. (2017), GFLI (2019), & Stoddart & Dimmock (2021). *Green dots indicate recent assessments using robust methodologies; amber dots indicate representative assessments, but either older data or lower sample size.

Findings

Greenhouse gas emissions from arable crops

1. Arable crops

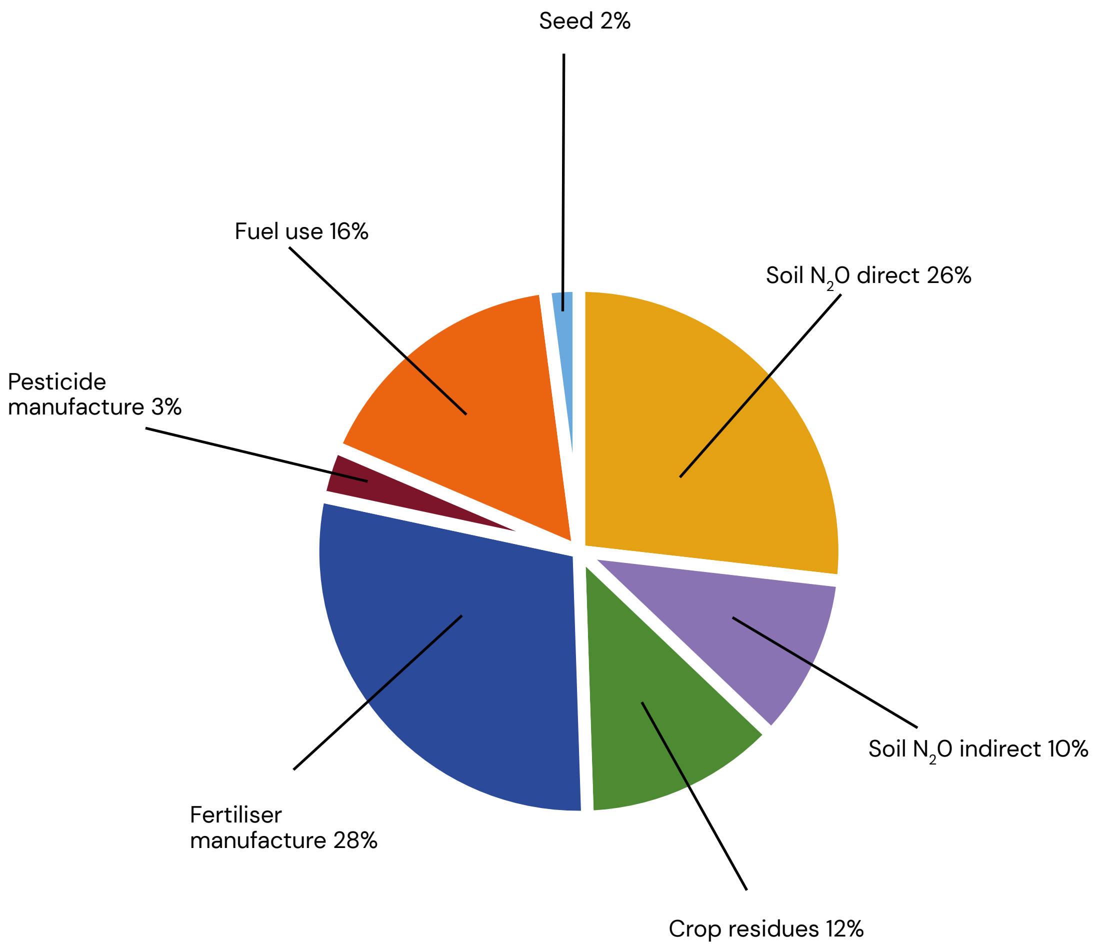
Data for GHG emissions from arable crops are robust, especially for the more widely grown cereals, albeit from studies using slightly different methods of analysis and assumptions.

One large study of 500 wheat crops, for example, showed an average of around 360kg CO_2e/t, with only a small number of the studied crops at the extremes.

Two factors interact with each other to drive greenhouse gas emissions in arable crops – the rate of nitrogen fertiliser use versus the yield. The lower the nitrogen use, the lower the embedded emissions from fertiliser manufacture and the direct and indirect emissions from soil, whilst a higher yield lowers the emissions intensity by factoring these emissions across a greater crop weight. The simple upshot of this interaction is that farmers who focus on resource efficiency will deliver the greatest emissions reductions.

The industry should focus on optimising yields through precision techniques, while minimising nitrogen use and maximising nitrogen use efficiency.

The Nitrogen Use Efficiency (NUE) of arable crops has the potential to act as a proxy measure for farmers to demonstrate ongoing progress towards net zero.



Top contributors to emissions in arable crops

- Nitrogen fertiliser manufacture
- Nitrous oxide emitted directly from soil denitrification
- Fuel use
- Crop residue management
- Nitrous oxide emitted indirectly via ammonia or nitrate pathways

Figure 1. Emission breakdown for conventionally produced feed wheat. The emissions intensity is 300 kg CO_2e/tonne. Data from Stoddart & Dimmock (2021).

Findings

Greenhouse gas emissions from arable crops

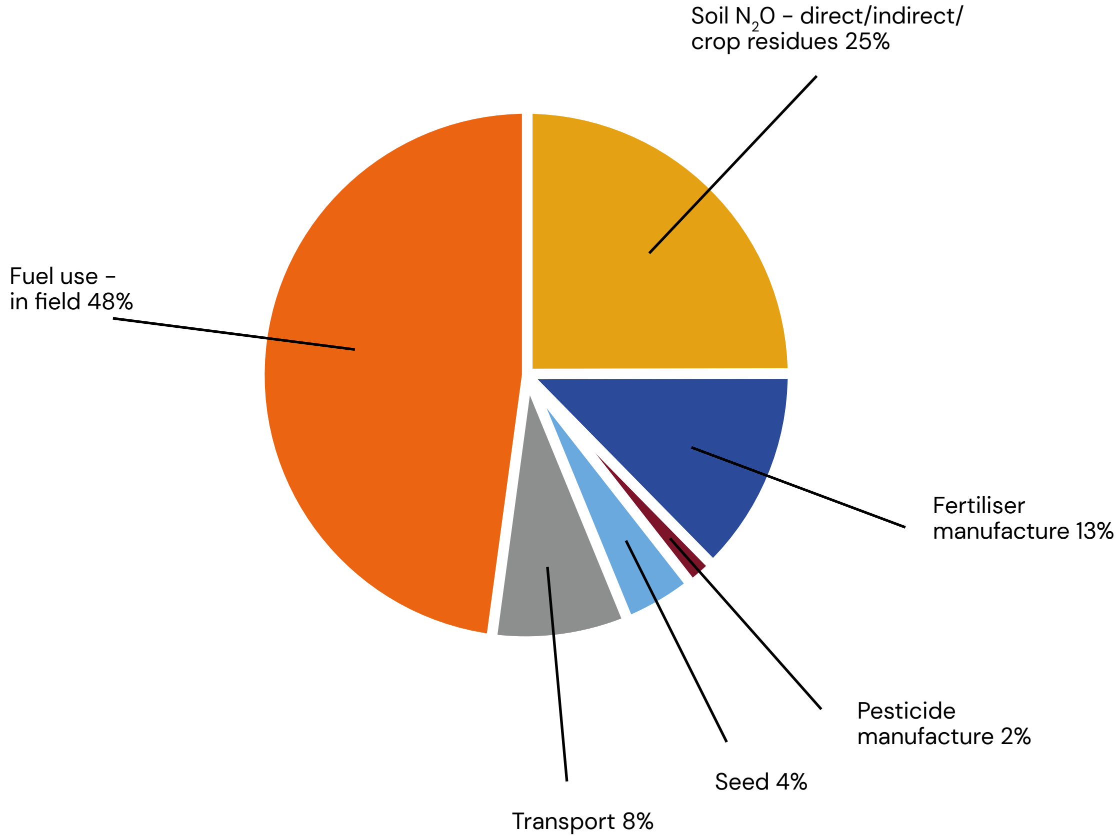
2. Legume crops

There is less data available for legume crops, such as field beans and vining peas, than for combinable crops, but UK-specific assessments of field beans and vining peas have been made.

Legumes can fix their own nitrogen and therefore require little, if any additional, nitrogen fertiliser. Legumes can be a useful in the rotation for building nitrogen in the soil for the next crop. As a result, UK legume crops have relatively low emissions per hectare, with the amount of non-nitrogen fertiliser used accounting for much of the variability seen between farm-level assessments.

Preventing further land-use change is vital for ensuring that the UK and global partners can achieve the goals set out in the Paris Agreement. A lack of embedded emissions from land use change for UK crops, means they have significantly lower emissions than some international comparators, such as soybeans from South America. It also removes the reputational risks associated with the use of soya.

The key focus areas for emissions reduction are around protecting yields through good integrated pest management and improving the fuel efficiency of management practices.



Top contributors to emissions in legume crops

- Fuel use in field
- Nitrous oxide from soil and crop residues
- Fertiliser, pesticide and seed manufacture
- Transport

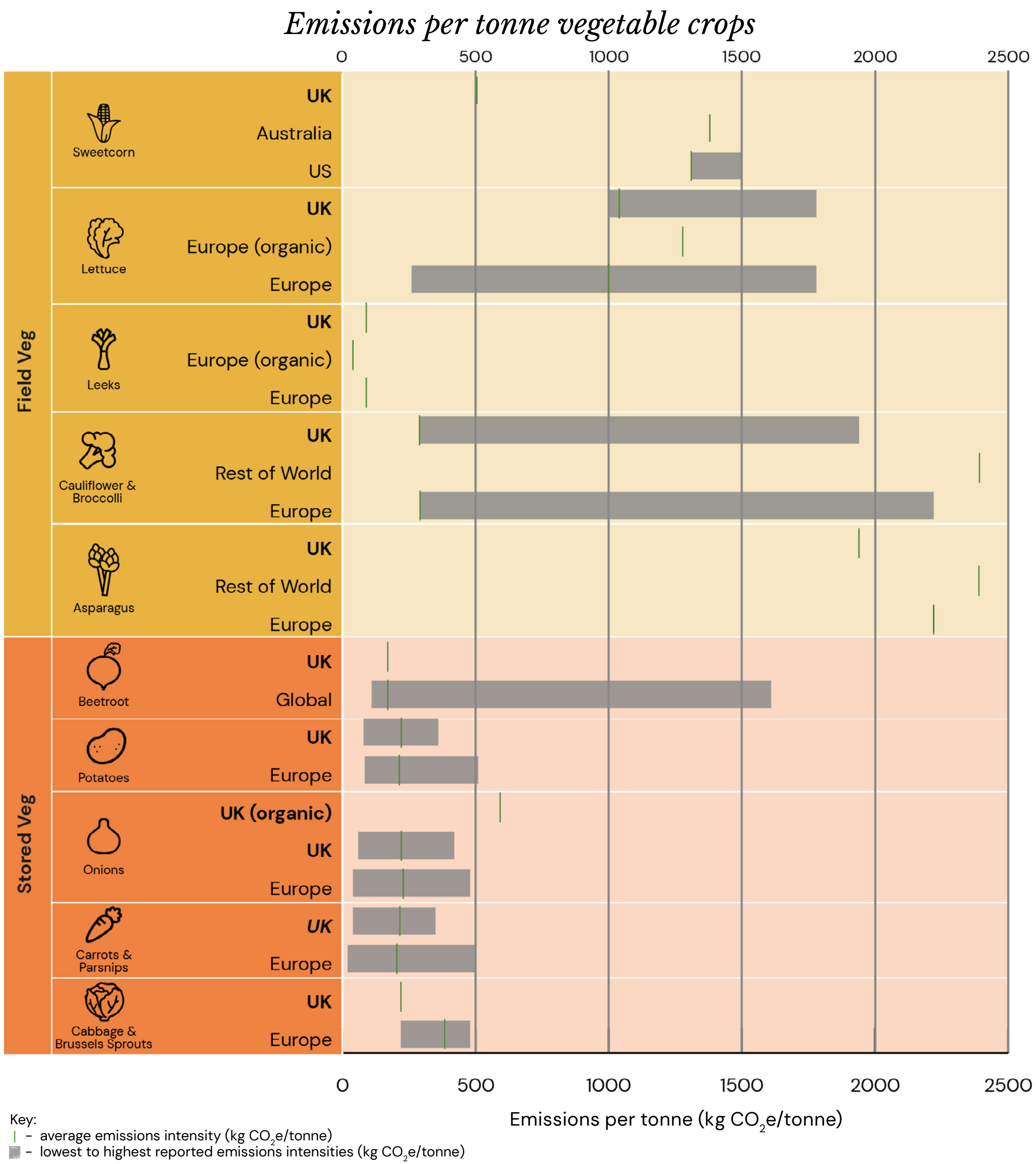
Figure 2. Emission breakdown for conventionally produced field winter beans. The emissions intensity is 96 kg CO_2e/tonne. Data from Wiltshire et al. (2009).

Snapshot

Greenhouse gas emissions from horticultural crops: vegetables

The horticultural vegetable sector has a lesser and more variable primary dataset, with some vegetables (e.g. parsnips and Brussels sprouts) having typically had proxy values assigned to them; the available data does allow us to define some benchmarks, but only with medium confidence.

Emissions intensities of between 90-505kg CO_2e/t are characteristic of the annual vegetables, with asparagus and lettuce being notably higher, principally due to the increased inputs required, particularly fuel, to produce these crops.



Emissions per tonne UK vegetable crops

Crop type	Benchmark UK emissions intensity (kg CO_2e/tonne)	Lowest reported UK emissions intensity (kg CO_2e/tonne)	Highest reported UK emissions intensity (kg CO_2e/tonne)	Degree of confidence in Benchmark*
Beetroot	170	-	-	● (amber)
Cabbage & Brussel Sprouts	200	-	-	● (amber)
Carrots & Parsnips	200	40	350	● (amber)
Onions	220	60	420	● (amber)
Potatoes	220	80	360	● (amber)
Asparagus	1940	-	-	● (amber)
Cauliflower & Broccoli	290	290	1940	● (amber)
Leeks	90	-	-	● (red)
Lettuce	1150	1000	1780	● (amber)
Sweetcorn	505	-	-	● (red)

Data for this snapshot is from a range of sources: Audsley et al. (2009), De Backer et al. (2009), Wiltshire et al. (2009), Maraseni et al. (2010), Foteinis & Chatzisymeon (2016), Clune et al. (2017), Miller (2017), Porter et al. (2018), Frankowska et al. (2019), GFLI (2019), & CONCITO (2021). *Amber dots indicate representative assessments, but either older data or lower sample size; red dots indicate that limited data exists or that the assessment poorly represents current UK production systems.

Findings

Greenhouse gas emissions from horticultural crops: vegetables

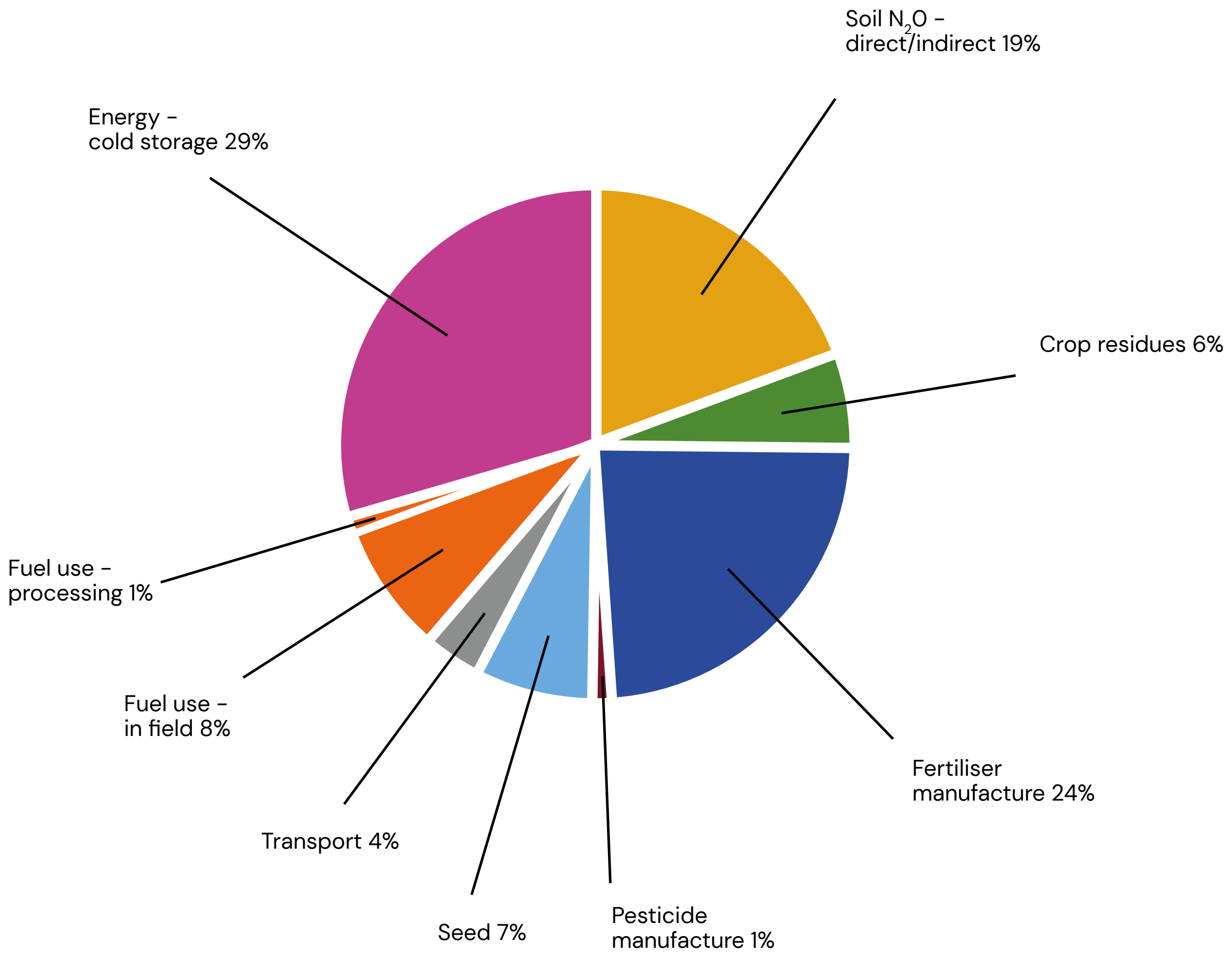
3. Vegetables with long-term storage

Crops such as potatoes, onions, carrots, parsnips, cabbages and beetroot all can have a long-term cold storage phase which is a key driver of emissions.

No single study compared multiple crops, but a review from multiple sources found similar emissions of 200-220 kg CO_2e/t for these crops, though there can be wide variation within a crop depending on whether they are sold fresh, when in the season they are harvested, and how long they are stored for.

As well as duration of storage, emissions for these crops are highly influenced by the type of storage (refrigerated or ventilated ambient), while in-field fuel use and nitrogen fertilisers are also major contributors to emissions.

Reducing emissions in stored crops rests with improving energy efficiency of stores, using renewable energy sources to power stores, and lessening cultivation intensity to cut fuel use.



Top contributors to emissions in long-term stored vegetables

- Storage, including energy source and refrigerants
- Nitrogen fertiliser emissions
- Fuel use in field and for processing
- Seed
- Crop residue management
- Waste

Figure 3. Emission breakdown for UK pre-pack potatoes. The emissions intensity is 149 kg CO_2e/tonne. Data from Wiltshire et al. (2009) updated to reflect current embedded emissions in N fertiliser (assuming emissions from manufacture have reduced by about 50% since the original assessment was made).

Findings

Greenhouse gas emissions from horticultural crops: vegetables

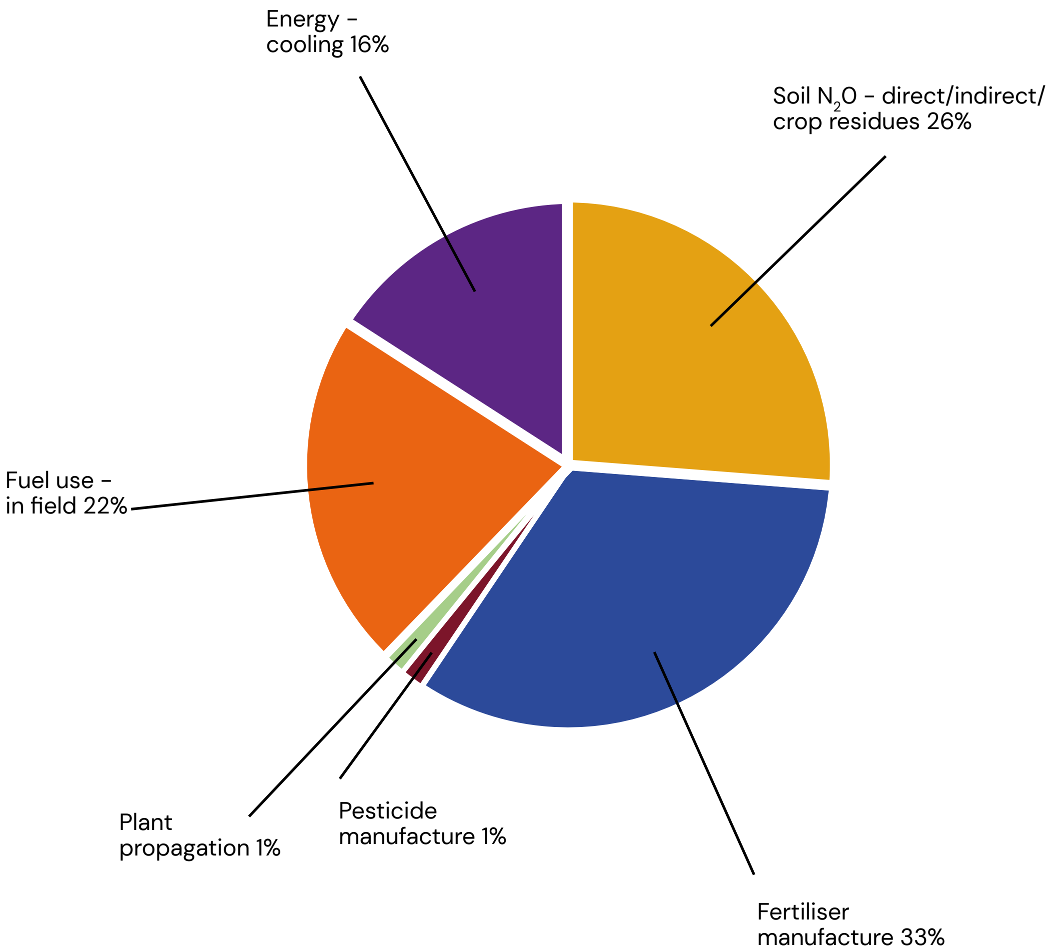
4. Fresh vegetables

Fresh field vegetables, such as leeks, sweet corn, asparagus, lettuce, cauliflowers, broccoli and Brussels sprouts generally have a short shelf life of 7-28 days, and similar emissions profiles.

Comparisons between crops are limited, but one older study collated emission intensities for most crops and found that nitrogen fertiliser manufacture and applications account for around 60% of emissions, with in-field fuel use accounting for another 20%. Energy use associated with post-harvest cooling and short-term storage is another significant contributor.

Crops such as asparagus and cauliflower have higher emissions than other vegetable crops because of lower yields per hectare and premium quality grading criteria. Although direct comparison is difficult because not all of the studies include post-harvest storage and refridgerated transport.

The type of production system used to grow fresh produce can also have a significant influence on total emissions. Variations in season length and climate between geographic locations can affect inputs such as irrigation and fuel use. Organic production systems, whilst typically having lower emissions per hectare, have been shown in some fresh vegetables, such as lettuce, to have significantly higher emissions intensities than conventional production systems due to their reduced yield.



Top contributors to emissions for fresh vegetables

- Nitrogen fertiliser and application
- Irrigation
- Fuel use in field
- Refrigerated transport
- Waste

Figure 4. Emission breakdown for conventionally produced outdoor lettuce. The emissions intensity is 83 kg CO_2e/tonne. Data from Hospido et al. (2009).

Snapshot

Greenhouse gas emissions from horticultural crops: fruit & protected

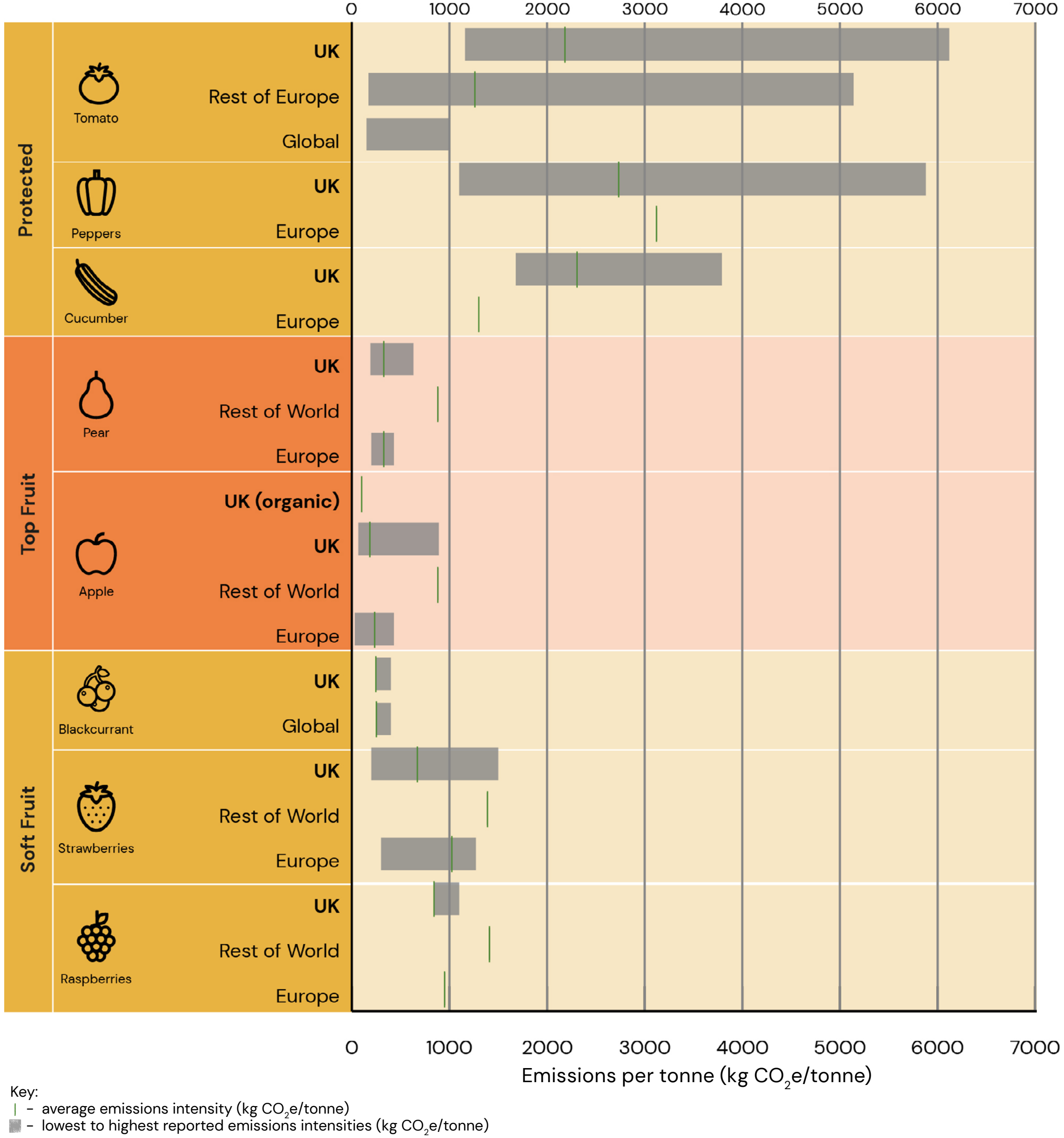
The fruit sector has a similar primary dataset to fresh vegetables, with the available data allowing us to define some benchmarks, but only with medium confidence.

The protected cropping sector shows very poor data availability, with no recent UK primary data publicly available; meaning that only low confidence benchmarks could be set.

The benchmarks set for these protected crops represent the average emissions intensities of highly-variable data, strongly affected by mode of heating and the presence or absence of lighting. These are areas in which more research is required and readers should treat this data with caution.

Emissions intensities of between 210-840kg CO_2e/t are characteristic of the fruit sector, with tree fruit being notably lower than the more intensively produced soft fruit crops.

Emissions per tonne fruit & protected crops



Emissions per tonne fruit & protected crops

Crop type	Benchmark UK emissions intensity (kg CO_2e/tonne)	Lowest reported UK emissions intensity (kg CO_2e/tonne)	Highest reported UK emissions intensity (kg CO_2e/tonne)	Degree of confidence in Benchmark*
Blackcurrant	250	250	400	● (amber)
Raspberries	840	840	1100	● (red)
Strawberries	700	200	1500	● (red)
Apple	210	66	890	● (amber)
Pear	320	190	630	● (amber)
Tomato	2110	1160	6120	● (red)
Peppers	2895	1100	5880	● (red)
Cucumber	2350	1680	3790	● (red)

Data for this snapshot is from a range of sources: Audsley et al. (2009), Wiltshire et al. (2009), ADAS et al. (2012), Hendricks (2012), Theurl et al. (2014), Clune et al. (2017), Porter et al. (2018), Frankowska et al. (2019), Van Grinsven et al. (2019) Torres Pineda et al. (2020), CONCITO (2021) & Marttila et al. (2021). *Amber dots indicate representative assessments, but either older data or lower sample size; red dots indicate that limited data exists or that the assessment poorly represents current UK production systems.

Top contributors to emissions for soft fruit

- Growing media
- Fertiliser
- Fuel use
- Post-harvest management
- Plastic materials
- Waste

Findings

Greenhouse gas emissions from horticultural crops: fruit & protected

5. Soft fruit

Published evidence for GHG emissions from strawberry and raspberry production is sufficient to set benchmarks for in-season production. The available UK data for blackcurrants is limited, and so corrected global data from analogous production environments has been utilised.

There are large differences in emissions between in-season production grown in ambient conditions, and out of season production where additional protection and sometimes heat is required to extend the picking season and maintain fruit quality.

Within the UK soft fruit sector, emissions generally arise from fertiliser and pesticide use, fuel use (both in-field and for post-harvest cooling and storage), materials and the growing medium (coir, peat, soil, perlite, etc.).

The key hotspots are driven by the production system used. Introducing energy efficient practices and the use of renewable energy will help reduce emissions.

Findings

Greenhouse gas emissions from horticultural crops: fruit & protected

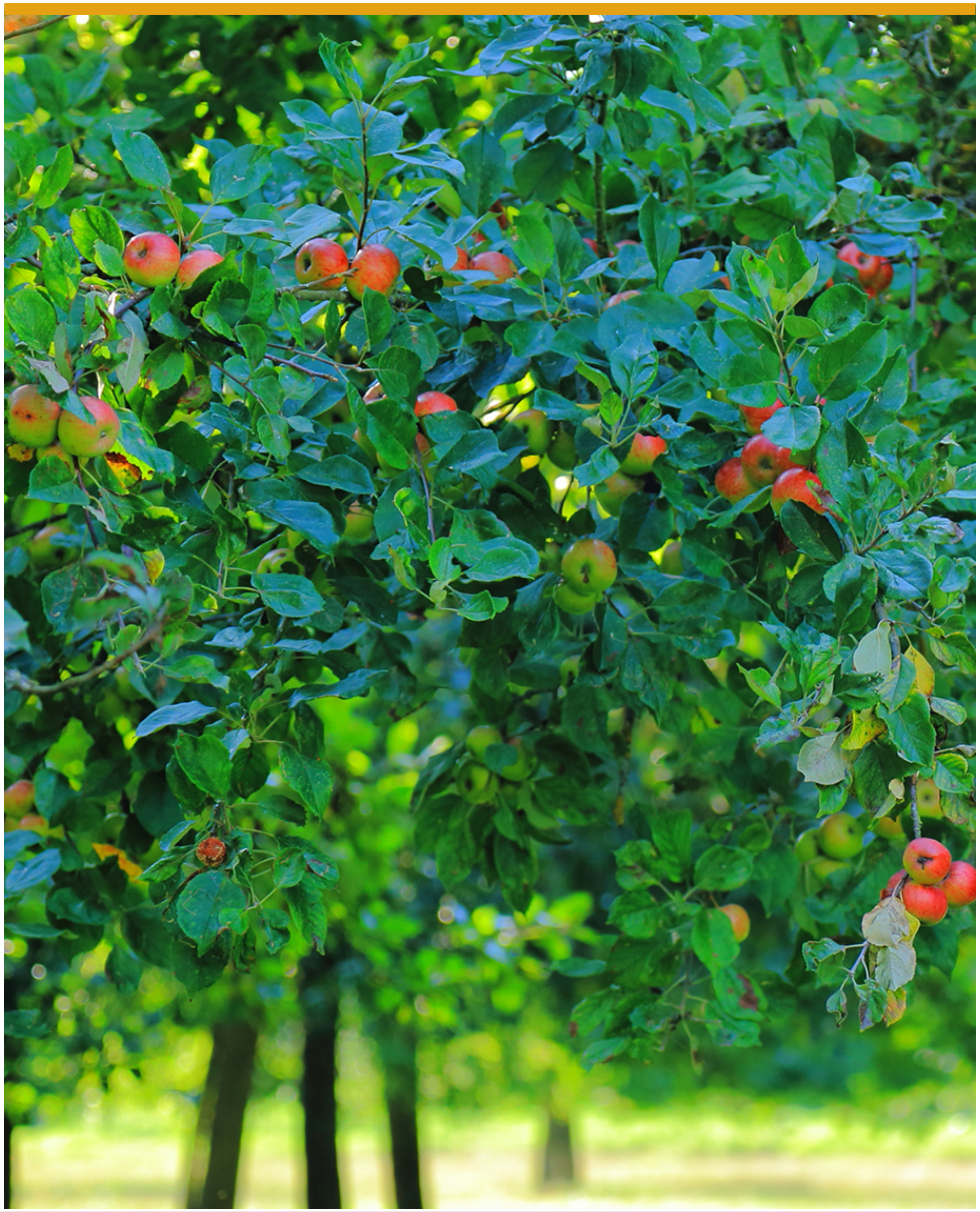
6. Top fruit

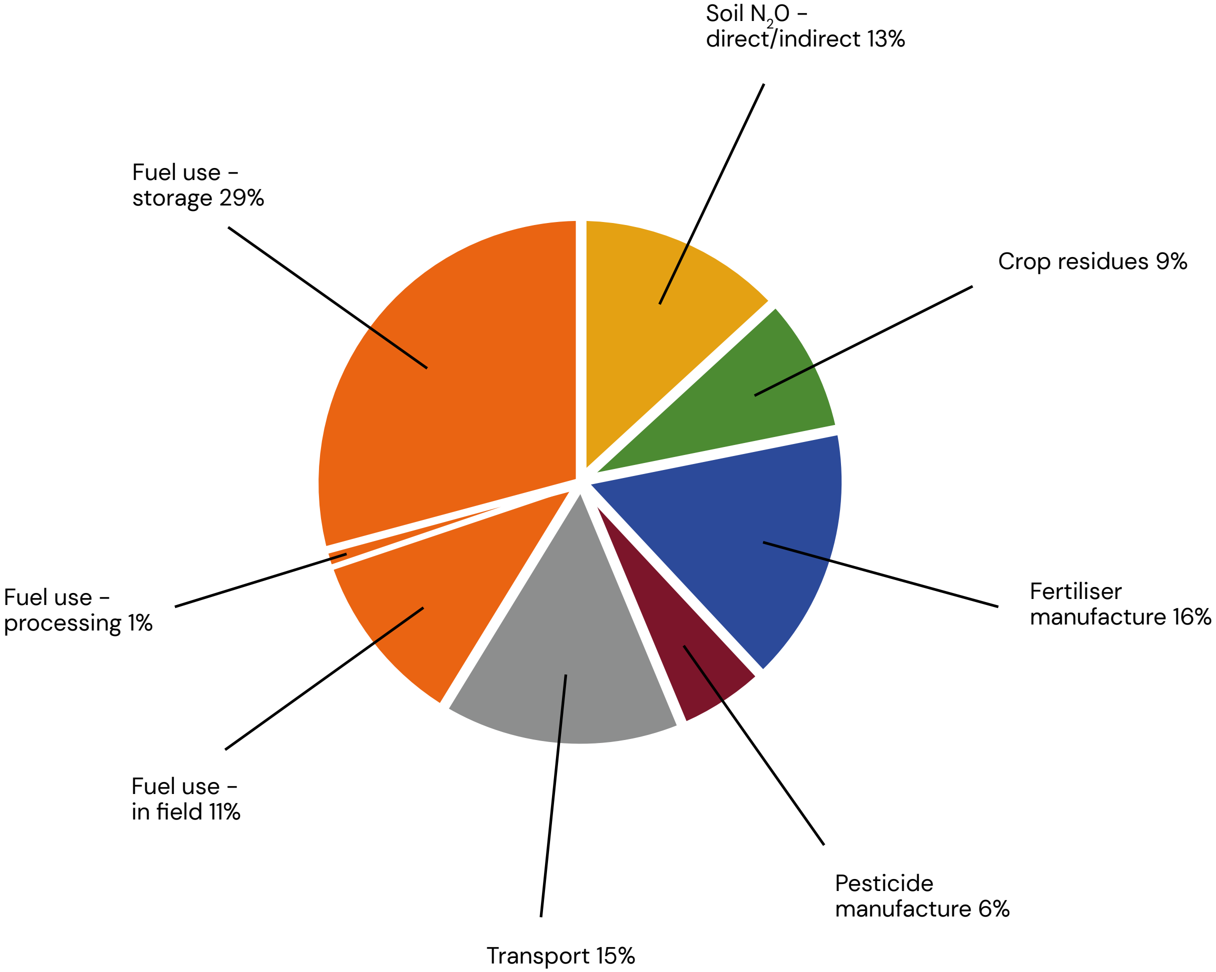
The key difference between top fruit and other crops is that they are a perennial crop, with orchards remaining productive for 15 years or more.

More data is available for apples, than pears or other orchard fruit, such as plums and cherries, with emissions relatively low as deciduous trees require relatively little nitrogen. Storage period will have an impact on emissions, as well as method of storage and energy source to power that store.

When calculating emissions, it is important to account for establishment and disposal emissions, and the impact of changing yields over the lifetime of the orchard.

Top fruit, like other high-value horticultural products, can be subject to high amounts of food waste, presenting a win-win opportunity for reducing food waste within the supply chain and with consumers. The top fruit sector also has the potential to sequester carbon, given the perennial nature of the trees, which presents a further opportunity for producers.





Top contributors to emissions for top fruit

- Fuel (storage and in field)
- Modified atmosphere storage
- Fertiliser and soil emissions
- Transport
- Crop residues
- Pesticides

Figure 5. Emission breakdown for UK intensively produced Cox apples. The emissions intensity is 62 kg CO_2e/tonne. Data from Wiltshire et al. (2009) updated to reflect current embedded emissions in N fertiliser (assuming emissions from manufacture have reduced by about 50% since the original assessment was made).

Findings

Greenhouse gas emissions from horticultural crops: fruit & protected

7. Protected crops (glasshouse)

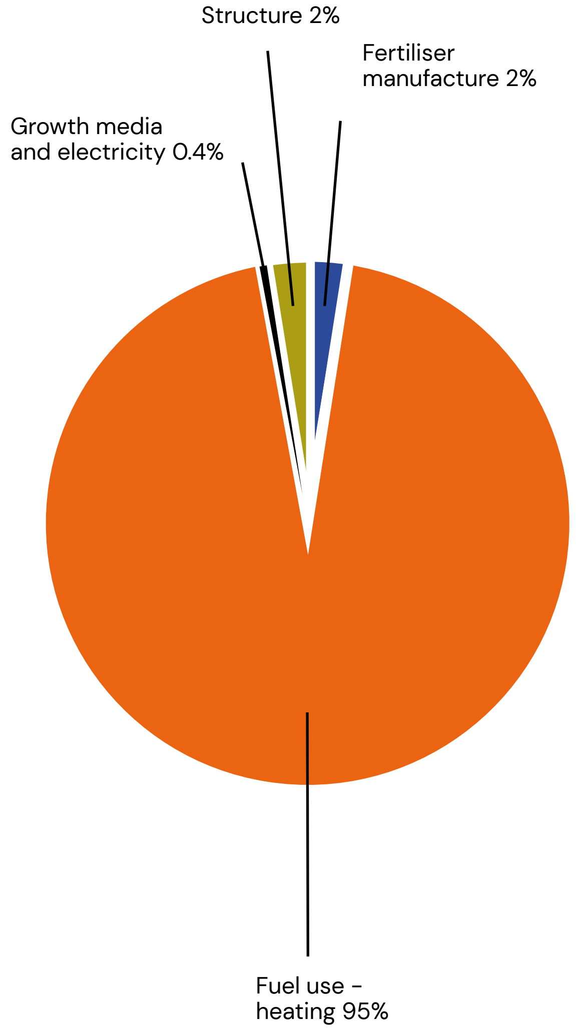
Protected glasshouse crop emissions are driven primarily by the heating, ventilation and CO_2 enrichment of the glasshouses, and to a lesser extent the lighting. The type of fuel used for heating can easily affect the emissions intensity of production by over 1000 kg CO_2e/t, for example.

The UK literature reviewed was found to be highly variable and collectively rather dated, so representative benchmarks could not be assigned based solely upon UK data. Given that glasshouse production systems share global similarities, proxy and modelled data from similar temperate climates were included to enable truer benchmarks to be set.

The emissions benchmarks for tomatoes, cucumbers and peppers are some of the highest values of all crops, due principally to the need for using considerable heat energy to create the correct growing conditions.

Whilst these benchmarks do represent the sector as a whole, it is acknowledged that almost half of the larger UK glasshouse growers are now using advanced biogas or biomass CHP plant for their heating and CO_2 supply, with some even pioneering industrial waste heat utilisation or solar electricity, meaning that values as low as 700 kg CO_2e/t (recently reported for Dutch tomato production) are likely achievable for some of these growers.

Improved energy efficiency and investment in renewable energy to provide heat, power and where possible carbon dioxide enrichment will be key targets for emissions reduction for the sector as a whole. Cost will be a key incentive for growers to adopt both alternatives to fossil fuels and energy efficiency improvements.



Top contributors to emissions in protected crops

- Fuel use
- Carbon dioxide enrichment
- Post-harvest handling and cooling
- Growing media

Figure 6. Emission breakdown for conventional tomatoes grown in Venlo glass greenhouse. The emissions intensity is 1928 kg CO_2e/tonne. Data from Torrellas et al. (2013).

Opportunities

Opportunities

How the crop sector can move towards net zero

To achieve net zero, the sector must both reduce emissions and enhance carbon removals from the atmosphere. It is imperative that emissions are removed from crop production as quickly and sustainably as possible, as this will significantly reduce the total amount of emissions that need to be mitigated.

Some actions to reduce emissions are outside the control of the farmer, such as reducing embedded emissions of inputs, while others are, such as selection of the type and source of inputs, and how they are used.

There are some consistent themes around emissions with the manufacture and use of nitrogen fertiliser affecting all conventionally produced crops to some degree, as does fuel, although a greater proportion of emissions are associated with fuel for some crops such as root vegetables and protected crops than others (e.g. cereals). Storage is essential for all crops, but electricity used for temperature-controlled storage is a key contributor.

As significant decarbonisation occurs across all sectors of the economy, there will be benefits for the cropping sector from increasing use of renewable electricity, innovations in transport and agricultural machinery to replace diesel, and low emission fertiliser manufacture.

But in the short- and medium-term, it will remain important for farmers to reduce their current emissions hotspots, optimise their systems and provide high quality crops.

Total elimination of emissions is unattainable because of a crop's biological need for nitrogen, so counter-balancing carbon removals are needed to achieve net zero. Embedded emissions in capital items, such as machinery and infrastructure, also need to be considered to achieve a net zero cropping system.

The cropping sector is well placed to counterbalance its residual emissions, with large areas of land available to manage agricultural production, vegetation and soils as short and long-term carbon storage – removing carbon from the atmosphere by 'nature-based' methods as well as engineered removals.

Some arable and horticultural farms may have greater opportunities than others to increase carbon removals, meaning that an overarching landscape approach could be considered, which targets farms to maximise benefits and minimise trade-offs, enabling farmers to deliver the most appropriate service.

For example, a highly productive farm producing high yields with low inputs may be best at focusing on production while minimising emissions, while a farm on less productive soils, requiring higher inputs or management to deliver yield, may be better at focusing its more marginal areas on carbon removal and providing a carbon balance to the higher productivity farm. Often the carbon benefits can be gained with wider biodiversity net gain opportunities that may deliver support from schemes such as the Sustainable Farming Incentive.

Two areas to focus on to reduce emissions on farm

1

Emissions related to nitrogen fertiliser use

GHG emissions related to the manufacture and use of nitrogen fertiliser make up the dominant contribution for many crops. Areas of focus to reduce emissions include optimising the amount applied, using technology to reduce emissions during and after application, and technology to reduce embedded emissions during manufacture.

Reducing embedded fertiliser emissions

- Use abated nitrogen fertiliser – production of nitrogen fertilisers (both ammoniacal nitrogen and urea) is a fossil-fuel energy-intensive process, while the use of nitric acid to produce ammonium nitrate leads to further emissions of nitrous oxide. European fertiliser production has lower GHG emissions than North American or Chinese produced fertilisers because of the increased use of nitrous oxide abatement technology. By asking suppliers what the embedded emissions are in their fertiliser, farmers can help reduce emissions.
- Low carbon nitrogen fertiliser – fertiliser manufacturer Yara is developing 'green ammonia' using hydrogen from renewable electricity, which could reduce embedded fertiliser emissions by as much as 30% and is predicted to be available post 2024.
- On-farm fertiliser production – a number of firms are developing manufacturing technologies, that should be available on farm in the longer-term, to reduce both costs and emissions. In California, Nitricity provides low-cost solar-powered plasma cells that produce fertiliser onsite by fixing nitrogen from the air. Atmonia from Iceland is developing a similar electro-catalytic process, while N2 Applied enhances the nitrogen content of organic materials on farm using nitrogen fixed from the air and reduces losses as ammonia.
- Fertiliser from anaerobic digestion – UK-based CCM Technologies is producing compound fertiliser from anaerobic digestate cake by drawing carbon dioxide from a chimney or biogas separator and flowing it through organic material coated with ammonia. In the longer-term this has the potential to reduce fertiliser manufacturing emissions by 90%.

Click for Case Study

Optimising nitrogen fertiliser use

Regularly soil test

Improves effectiveness of fertiliser applications. If soil is too acid or alkaline it can reduce the effectiveness of fertiliser applications.

Use more nitrogen-efficient crop varieties

Breeding has only made small improvements in nitrogen use efficiency (the amount of yield per unit of available nitrogen), approximately 0.3% per year, so there is an opportunity to increase the rate of improvement, although much R&D is required so this is unlikely to be a quick win.

Adopt more precision fertiliser application

Use of GPS guidance systems minimises overlap during application, while sensors that measure crop and soil parameters in the field, allowing the rate of nitrogen to be automatically adjusted as it is applied, help optimise applications. Incorporating fertiliser under the soil surface can also cut nitrous oxide emissions in reduced tillage systems.

Include legumes in rotations

Growing legumes as either break crops, part of a ley or under sowing into existing crops can reduce nitrogen fertiliser need, avoiding emissions produced in manufacture.

Use nutrient management plans

Incorporates where, when and at what rate different types of fertilisers can be used. Estimated to save 0.02–1.42t CO_2e/ha/year.

Reduce nitrogen fertiliser application emissions

Use low emission spreading for slurry

Conventional application of slurry from a tanker onto a splash plate can be improved through use of alternatives such as trailing hose or shoes that deliver the slurry onto the soil surface or below the crop canopy, or shallow or deep injection systems where the slurry is inserted into a slit in the soil created by discs or tines. These methods reduce ammonia emissions, although direct nitrous oxide emissions can be increased particularly when soils are wet.

Use urease inhibitors

These reduce ammonia emissions from urea by delaying the breakdown of urea into ammonium, giving greater time for plants to take up the fertiliser.

Use nitrification inhibitors

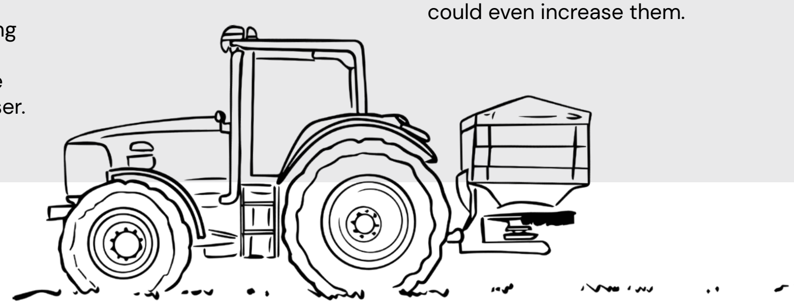
These chemicals slow the conversion of nitrogen fertiliser into nitrous oxide. Incorporated into manufactured fertiliser or applied as standalone products, the ~25% increase in cost is a barrier to uptake. Whilst efficacy is impacted by factors such as pH, soil temperature and moisture, there is good evidence of their effectiveness when used correctly (studies suggest a 29-39% reduction of nitrous oxide emissions on average, for cropland), and they also have the potential to reduce split applications, lowering fuel use.

Use slow-release fertilisers

Coated in a polymer that reduces the rate bioavailable nitrogen is released to the environment, studies show a 35% reduction of nitrous oxide emissions on average, although effects vary by soil type.

Rapidly incorporate organic manures

Manure application releases ammonia, so incorporation within 24 hours is recommended, reducing indirect emissions. The effect on direct nitrous oxide emissions is less clear, and it could even increase them.



Two areas to focus on to reduce emissions on farm

2

Reduce Fuel Use

Fuel use, whether in the field, glasshouse, post-harvest or in storage is another major contributor of emissions. Farmers can make the following changes to reduce use.

a) Arable

In field

- Reduce cultivation intensity – moving soil increases fuel use. In combinable crops, any move to reduce cultivation intensity from eliminating or using the plough fewer times, to direct drilling will reduce fuel use.

  In vegetable and especially potato systems reduction of cultivations is more difficult as it is required for seedbed quality and weed suppression, but an AHDB study found destoning at depths of 22-28cm compared with the commercial depth of 30-38cm reduced fuel use by 35% without any difference to yields.

  Strip tillage, where a strip is cultivated for the crop to be planted into, with the interrow space left uncultivated, is an option for row crops such as wheat, maize, sugar beet and some vegetables. The system uses less fuel than conventional systems, but more than zero tillage.

- Use enhanced automation - automation of labour-intensive operations such as weed control and harvesting sensitive fruits by lightweight, electrically powered robots can reduce emissions if this replaces tractors and heavy machinery reliant on fossil fuels. There may be trade-offs if replacing manual tasks, whereby the embedded emissions from robots and any fossil fuel energy required to power them could increase emissions.

- Use alternative tractor fuel types – the majority of tractors are powered by diesel. While energy efficiency of these engines has been improved, and steps taken to reduce emissions from combustion, in the longer term alternative fuel types are likely to have a bigger impact. Alternatives include electric traction, although there is concern over battery life, hydrogen, biomethane and ammonia.

- Improve energy efficiency of irrigation – through improving the energy efficiency of the system, and improving water use efficiency so less water is needed to be pumped. Options to reduce emissions include using pumps powered by renewable energy, switching to drip irrigation, irrigating according to crop needs and using variable rate irrigation.

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b) Horticulture

Reduce fuel use post-harvest and in store

- Install renewable electricity – renewable electricity has lower emissions than grid electricity. On farm renewable electricity could come from solar photovoltaic panels, wind turbines, anaerobic digestion with combined heat and power boilers, or heat pumps.

- Fix leaks in cold stores – air leakage increases energy consumption by requiring increased refrigeration and / or ventilation to maintain the optimal temperature and humidity. One study of potato cold stores found this accounted for 55% of energy consumption. Identifying and repairing leaks is a reasonably easy and cost-effective way to reduce energy consumption.

- Improve insulation in cold stores – good insulation prevents heat entering cold stores and reduces energy consumption. Older stores are more likely to have insufficiently thick or poor quality insulation. Upgrading can also help with air leakage. Adding a further 50mm insulation to a cold store with 50mm already installed could reduce both energy consumption and emissions by 12%, a computer simulation suggested. While not cheap, typical payback is attractive at under 3 years.

Reduce fuel use in glasshouses

- Use alternative fuel for heating and CO_2 enrichment – currently most tomato and pepper production involves burning of natural gas in combined heat and power boilers, and accounts for 90-95% of GHG emissions. The two main alternatives are biogas and biomass – both have considerably lower GHG emissions.

- Install active heat storage – in glasshouses there is a mismatch between the crop's requirement for carbon dioxide for photosynthesis during the day and heat at night. Commercial growers use water tank storage to store heat during the day and release it at night, which involves the use of heat pumps. Alternatives to this include phase-change material storage (similar principle to water tank storage) and large-scale underground heat storage systems, which can store excess summer heat and release it during winter to extend the growing season.

- Passive heat storage – constructing a north wall to capture solar energy that predominantly enters from the south during the day. The wall releases the heat as the temperature falls at night – reducing heat energy use by 35-50%.

- Install thermal screens – these false ceilings prevent cold air falling onto crops, and heat leaving through the roof. While they can achieve 20-35% saving in energy, there is likely to be minimal additional gains as they are already widely used.

- Install automatic climate control – temperature and humidity in glasshouses can be controlled either manually or automatically using a range of sensors. Evidence is limited about impact of increasing automation.

- Implement temperature integration – this is another form of climate control, which requires automatic temperature control before it can be used. When outside conditions are unfavourable, for example, windy or cloudy, heat is lost from a greenhouse at an increased rate. Under these conditions, the temperature set point can be lowered until conditions improve when the temperature set point is increased to ensure the daily average temperature remains optimal. This could save 30% in energy consumption during the winter.

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Positive actions for the sector

Arable

Challenge	*Farmers & Growers*	*Supply Chain*
Crop residue management	Incorporate within soil or look at additional beneficiation options.	Use residues for biofuels, composts, livestock bedding or feeds; improve biomass supply chain management.
Fuel & transport	Optimise cultivation techniques, consider min-till and controlled traffic approaches and limit tractor usage over short distances.	Ensure vehicles are efficient, increase biofuel availability or switch to electric powered machinery, pre-plan routes and use refrigerants with low GHG potential.
Fertiliser, pesticide and seed manufacture & use	• Apply precision techniques and nutrient planning (incl. soil testing) to reduce agrochemical and nitrogen applications • Increase use of organic materials to displace artificial fertilisers • Develop genetics of arable crops to increase efficiency, with less available N	• Reduce embodied carbon in products and make that information available to farmers/supply chain • Address retail specifications that encourage overapplication of inputs

Horticulture

Challenge	Farmers & Growers	Supply Chain
Crop residue management	• Prevent, detect and manage pest and disease in line with AHDB IPM recommendations • Apply precision techniques and nutrient planning to reduce agrochemical and nitrogen applications • Improve irrigation control and efficiency in line with AHDB guidance	• Reduce embodied carbon in products and make that information available to farmers/supply chain • Collate data for water footprint and opportunities to optimise and reuse water
Fuel & transport	Optimise cultivation techniques, consider min-till and controlled traffic approaches and limit tractor usage over short distances.	Ensure vehicles are efficient, increase biofuel availability or switch to electric powered machinery, pre-plan routes and use refrigerants with low GHG potential.
Waste & post-harvest management	• Increase use of out-of-specification produce in feed or on-farm AD-plant to generate energy • Incorporate crop residues within soil or look at other beneficiation options • Reduce use of plastic and aim to source recycled plastics or alternatives	• Review specification for food & increase consumer acceptance of 'wonky produce' and minor blemishes • Utilise crop residues for biofuels, composts, livestock bedding or feeds • Increase take-back and recycling of agricultural plastics; explore alternative packaging solutions
Storage (Incl. energy Source & refrigerants)	Consider the economics of using passive systems to cool/store the produce or the installation of solar PV/ other renewable technologies to deliver savings.	Use refrigerants with low GHG potential and maintain to avoid leaks.

Protected Cropping

Challenge	*Farmers & Growers*	*Supply Chain*
Growing media	• Transition from peat-based growing media • Support development of novel, sustainable growing media • Develop on-site reuse and recycling strategies	• Develop recycling technologies for organic-contaminated rockwool • Explore new value chains for recycled materials
CO_2 enrichment	• Consider the economics of CO_2 filtration and use from on-site biomass or biogas production • Focus on reducing ventilation to maximise CO_2 usage rate	Improve co-location of businesses to optimise supply and demand efficiencies for CO_2 use.
Energy use	• Explore the installation of renewable technologies to deliver savings • Consider the economics of passive thermal storage or heat exchanging technologies • Regular maintenance and optimisation of ventilation and shading	Ensure vehicles are efficient, increase biofuel availability or switch to electric powered machinery, pre-plan routes and use refrigerants with low GHG potential.
Post-harvest handling & cooling	• Harvest products during the cool part of the day • Consider the economics of using passive systems to cool/store produce • Explore technologies to optimise harvest time/quality	• Maintain the cold-chain to avoid excess cooling • Integrate new technologies to minimise post-harvest losses

Five ways farmers can increase soil carbon at the field level

1

Reduce tillage intensity

Increasing soil carbon on farm is not simple, with lots of interacting and conflicting variables making quantification of the impact of practices uncertain. It is important to remember the need for permanence or dynamic stability (long-term storage), to understand when saturation occurs (there's a finite amount of carbon that can be stored in soils), and to consider the impact of actions on leakage (moving carbon from one location to another). So how can farmers potentially increase carbon sequestration at a field level?

Reduced cultivation intensity is generally considered to lead to an increase in soil carbon due to a decrease in soil disturbance, and hence exposure of organic matter to decomposition. However, evidence is mixed partly because its impact is difficult to quantify and also because reducing cultivations changes where carbon is deposited in soils, with minimum tillage favouring carbon storage in surface layers, while ploughing incorporates carbon in deeper topsoil layers.

One evaluation of long-term tillage experiments in the UK reported an annual increase in soil organic carbon from zero tillage of 310 kg C/ha/year (± 180 kg/ha/year), although the wide variation meant this was not significantly different from zero.

Soil type and rotation are important factors for whether it is feasible on farm. No-till is less suitable for lighter soils because of the risk of soil capping, while any soil structural concerns should have been rectified before adopting, e.g. alleviating existing compaction. Where no-till is implemented, it is important the practice is maintained to avoid loss of accumulated soil carbon.

Potential Benefits

- Increased water infiltration and retention
- Reduced soil erosion
- Reduced leaching
- Lower powered tractors & reduced fuel use
- Increased soil biodiversity
- Quicker field preparation & lower labour costs

Potential Risks

- Short-term yield loss
- Potential investment in new equipment
- Less opportunity in root crops
- Not always suitable during poorer weather
- Increased disease and grass weed risks leading to increased reliance on chemical control

Five ways farmers can increase soil carbon at the field level

2 Establishment of cover crops

Cover crops are non-cash crops incorporated into the main crop rotation, and help maintain soil cover to protect against erosion while capturing nutrients. They also return additional organic matter to the soil. Various studies suggest between 590 and 1,760 kg CO_2e/ha/year could be added to soils. Whether the crop is grazed, and therefore converted to manure, or how it is destroyed prior to planting the next crop will influence carbon capture.

Identifying the primary purpose of the cover crop – capturing nutrients, improving soil structure, increasing soil fertility or soil organic carbon – is crucial for success, plus identifying the appropriate species mix and management for the soil type, rotation and climate.

As a relatively recent addition to rotations, experience is showing that early establishment of cover crops and carefully managing the transition to the following crop are important. Early destruction (3-6 weeks) and desiccation has proven essential in some situations, particularly on heavier soil types before drilling a cash crop, or to avoid increased pest or disease pressures.

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Potential Benefits

- Protect soils from erosion
- Reduce nitrate leaching and phosphorus losses
- Improved cereal and potato yields
- Additional source of income if grazed
- Legumes in cover crops can reduce N requirements in following cash crop

Potential Risks

- Extra costs from seed and management
- Increased slug and weed pressure (not consistent)
- Higher nitrous oxide emissions, particularly for legume only cover crops
- Green bridge for pests and diseases (depending on management)
- Better ahead of spring than autumn crops, but spring crops yield less

Five ways farmers can increase soil carbon at the field level

3

Incorporation of crop residues

Evidence shows the incorporation of crop residues – rather than being baled and removed from the field – on average does lead to carbon sequestration. The increase is small and, in some situations, might not lead to a noticeable difference compared with removal.

Data from five long-term experiments in England suggest an average carbon sequestration of 44 ± 8 kg C/ha/year/t of straw applied; using an average straw yield (3.4 t/ha at the time of the report) equates to 150 kg C/ha/year, they say.

Straw can be used to produce bioenergy through burning, and displacing fossil-fuel-based energy production, minimising greenhouse gas emissions. A study suggests this has a net benefit for GHG emission reduction provided that crop residues are not removed every year.

Potential Benefits

- Reduce applied nutrients required for following crop
- Reduces risk of compaction
- Improves soil physical characteristics

Potential Risks

- Foregoes income from selling straw. Limits straw supply to livestock sector.
- Increase nitrous oxide emissions (depends on how removed straw is used as that can also release nitrous oxide).
- Can temporarily immobilise nitrogen by stimulating microbial activity, but consistent incorporation and maintaining a good C:N ratio can reduce the potential for immobilisation.

Five ways farmers can increase soil carbon at the field level

4

Incorporate livestock manures and slurries

Incorporating livestock manures and, to a lesser extent, slurries is generally associated with an increase in soil carbon. Animal manures contain a high proportion of carbon, so their incorporation within soils increases soil organic carbon (SOC) stocks and can act as a form of carbon storage, though soil, agronomic and environmental factors do affect the magnitude and permanence of this effect.

Farmyard manure – solid manures mixed with bedding materials – have greater positive impact on soil organic carbon than liquid slurries with limited bedding. An assessment of long-term UK experiments found livestock manures change SOC by 60 ± 20 kg/ha/year/tonne manure dry solids applied equating to 630 kg/ha/year at typical application rates.

Applying manures must comply with stipulated legislation and Codes of Practice to minimise impact of the environment, watercourses and biodiversity. Careful management before application can reduce the amount of ammonia released (indirectly leading to nitrous oxide emissions) and direct nitrous oxide losses.

But where manures are moved from one farm to another there is the risk of leakage of carbon with the exporting farm losing soil carbon while another gains. With the majority of livestock manures applied to soils already, there is a limit to its potential, although technologies to optimise the nutritive values of manures and slurries do offer an opportunity to do more with less.

Potential Benefits

- Improvement in nutrient cycling
- Improved soil structure and stability
- Improved water holding capacity and infiltration
- Reduce applied nutrients required in following crop

Potential Risks

- Nitrous oxide emissions
- Air and water pollution if not stored or applied correctly
- Cross-contamination issues, e.g. manures carrying weed seeds.

Five ways farmers can increase soil carbon at the field level

5

Incorporate high organic carbon materials

Other organic materials, such as biosolids, composts, paper crumble, water treatment cake, industrial wastes and digestate from anaerobic digestion are also added to soils, although use is restricted by regulation and availability.

Biosolids in long-term trials in the UK have been shown to increase soil organic matter by 10-17% over 20 years (approximately 1200-2200 CO_2e/ha/year) relative to land treated solely with manufactured fertilisers.

Similarly, application of digested biosolids, green compost and paper crumble increased soil organic carbon by 5,500, 5,130 and 6,600 kg CO_2e/ha/year respectively. Much of this material is already used as soil amendments, so in most cases this is not adding further carbon sequestration beyond business as usual, although there are additional sources that could potentially be exploited.

Potential Benefits

- Improvement in nutrient cycling
- Improved soil structure and stability
- Improved water holding capacity and infiltration
- Reduce applied nutrients required in following crop

Potential Risks

- Nitrous oxide emissions
- Air and water pollution if not stored or applied correctly
- Contamination risks from PTEs, plastics, antibiotics and heavy metals

Opportunities

Smaller-scale farm-level land use changes for carbon removal

Potential Benefits

Improves biodiversity, especially bird and insect species

Acts as wildlife corridors linking fragmented habitats

Improves soil aggregate stability, hydraulic conductivity, and earthworm activity

Lowers bulk density

Potential Risks

Planting and maintaining hedges incurs additional cost

Weed burden may encroach into the arable field

1. Managing hedgerows

Other more intensive actions changing how land is managed at a farm-level can also potentially remove carbon from the atmosphere. The following are all compatible with maintaining some level of production.

Hedges are an effective form of above-ground carbon storage, with additional benefits for biodiversity, soil erosion and flood management, and growing evidence for increasing soil carbon below ground. The benefits from existing hedgerows can be increased by allowing increased height and / or width, as well as filling gaps in hedges.

Poorly managed hedges with big gaps and thin plants will contain much less carbon, and fewer other benefits. Filling gaps in existing hedges and improving hedge health should be pursued as well as establishing new hedges.

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Opportunities

Smaller-scale farm-level land use changes for carbon removal

2. Introduce rotational leys

Including rotational grass / clover leys on a two- or more-year rotational cycle offers the opportunity to build soil carbon. While currently more common where mixed farming dominates, the use of rotational leys is expanding in specialised arable production areas.

An estimated 560 kg CO_2e/ha/year of carbon could be sequestered and stored if grass leys were incorporated as a one-year in four rotation, while research literature suggests grass-arable rotations may capture 950 – 1320 kg CO_2e/ha/year, but little consideration is given to the duration over which that carbon is captured and its permanence.

Disturbance of soil at the end of the ley to prepare the following crop will expose some of the accumulated carbon to oxidation leading to a loss of soil organic carbon, but using reduced tillage can reduce this impact.

Uptake by farmers in cereal areas is likely to require suitable financial incentives.

Potential Benefits

- Potential income from livestock
- Better weed control
- Improve biodiversity
- Improvement in soil health, leading to potential yield improvements

Potential Risks

- Loss of income from cash crops
- Costs for bring livestock onto farm, especially for first time
- Gaps potentially required between ley and horticultural crops

Opportunities

Smaller-scale farm-level land use changes for carbon removal

3. Establish permanent buffer zones

There is robust evidence that soil within buffer strips – areas of permanent vegetation around the edge of fields or adjacent to water courses – has higher soil organic carbon than adjacent arable land. These areas are primarily used to prevent pollution from run-off, but also have important benefits for biodiversity.

Most margins tend to be supported through agri-environment schemes, so ongoing support to maintain these valuable carbon stocks is required.

Potential Benefits

- Provide habitat for biodiversity
- Reduced pollution of water courses
- Increased water holding capacity
- Improved soil structure including increased aggregate stability and lower bulk density

Potential Risks

- Can increase difficulty of field management
- Reduction in income from reduced land area – fixed costs spread over smaller area

Opportunities

Smaller-scale farm-level land use changes for carbon removal

4. Implementing agroforestry

Integrating trees into cropping and livestock systems can increase soil carbon sequestration and storage, as tree roots modify the quality and quantity of below-ground carbon inputs and recover nutrients and moisture from depth. Some studies show agroforestry can increase crop yields, system resilience and alter microclimates, but trees also compete with crops for light and water, so optimising the system requires careful matching of tree species and crop type.

One study estimated the soil and above-ground carbon sequestration potential in an arable agroforestry system to be 8840 kg CO_2e/ha/year.

Potential Benefits

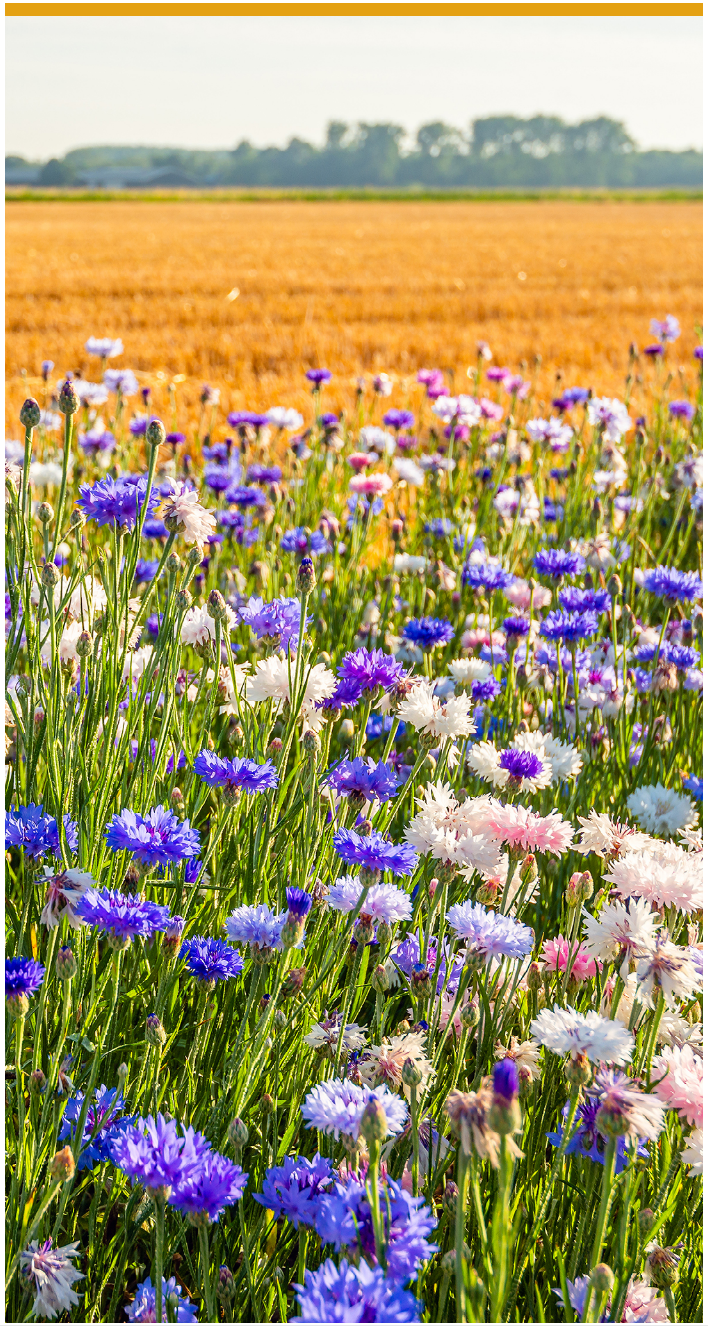
- Improved soil structure
- More effective use of nutrients from soil profile
- Better biodiversity outcomes
- Additional income from trees
- Reduced soil erosion

Potential Risks

- Lower overall crop productivity
- Limit machinery accessibility, increasing fuel use and reducing efficiency

Opportunities

Smaller-scale farm-level land use changes for carbon removal



5. Mantaining existing soil organic carbon

Alongside increasing carbon stores, it is also crucial to reduce the risk of stored carbon being lost. Of particular importance is loss of soil organic matter from soil erosion caused by wind and water, which potentially accounts for up to 50% of soil carbon change, a review suggests.

Some of the practices above, such as cover crops, establishing hedgerows and buffer strips, reduce the flow of water across soil and provide a break against wind erosion, and will help reduce erosion as well as increase carbon sequestration.

In addition, the following can help reduce soil erosion and protect carbon stocks, but not sequester carbon themselves:

- Cultivate compacted soil
- Leave autumn seedbeds rough
- Cultivate across the slope
- Manage over-winter tramlines
- Early establishment of winter crops

6. Innovative practices to increase carbon storage in soils

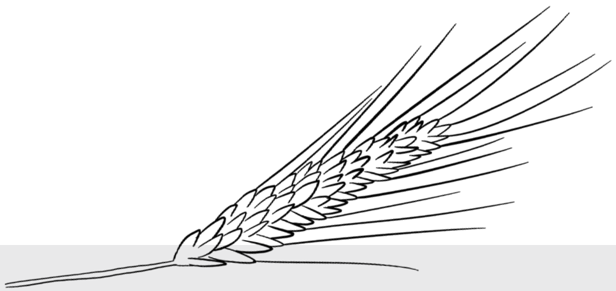
- Biochar addition to soil – currently subject of research on large-scale field trials
- Enhanced mineral weathering – currently subject of research on large-scale field trials
- Crop breeding for increased carbon sequestration – in the longer term

Recommendations

Recommendations

Summary

Reaching net zero in arable and horticultural crop production will require agriculture to reduce its emissions as much as possible while balancing its remaining emissions through carbon removals (sequestration).



Evidence for quantifying emission reduction is more robust and consistent than for some kinds of carbon removals, though there is currently a considerable research and innovation focus on greenhouse gas removals, an almost unique attribute of the agricultural sector. The emphasis should be on reducing greenhouse gas emissions as much as possible, with carbon removals used to provide a sufficient overshoot or 'headroom' in sequestration to counter the present levels of uncertainty.

Emissions come from three main sources: embedded emissions in nitrogen fertiliser manufacture, emissions (direct and indirect) from soil nitrogen dynamics, and energy use on farm.

In arable crops reducing emissions due to nitrogen fertiliser is more important, while in horticulture, especially where stored long term or produced in a glasshouse, energy production is of higher importance.

Reducing emissions is closely linked to production – an optimal low-carbon production system aims to minimise inputs, especially fertiliser and fuel, while maximising yields. Agronomic improvements, such as improvements to integrated pest management, genetics, reducing waste and general attention to detail will help decrease emissions per tonne of production.

To drive reductions in climate impact, actions need to reduce emissions per hectare of production, while either maintaining or increasing production.

Changes in technologies around low-carbon fuels, energy generation and supply, and the manufacturing of nitrogen fertilisers will help reduce embedded emissions associated with crop production.

Reaching net zero, while not easy, is an achievable ambition across the sector. Improvements in efficiency, both in terms of yield and resources, do have the potential to significantly reduce emissions. In the medium-term, new technologies are likely to decarbonise some of the embedded emissions in raw materials brought onto farm, while in the longer term looking at how land is used and optimising production may offer bigger opportunities to remove carbon. Funding mechanisms, either through public or private schemes, will be needed, with innovation pathways carefully monitored to ensure that the right practices are adopted and implemented in the right places.

Recommendations

Recommendations for setting net zero goals

For farmers and policy makers, the following seven recommendations are areas to focus on:

1. Encouraging selection of nitrogen fertilisers based on their embedded emissions. Ensure that as lower emission nitrogen fertilisers are developed, tested and proven to be safe and effective, they are taken up by the industry.

2. Optimising nitrogen applications by utilising alternative sources of nitrogen such as manures, organic materials and legumes to minimise need for manufactured nitrogen fertilisers. Utilising precision technologies to enhance the accuracy of nitrogen placement to improve nitrogen use efficiency in the crop and reduce total requirement as well as risk of losses. Adapt nutrient management guide RB209 accordingly.

3. Using new technologies to reduce emissions from nitrogen fertiliser application including the use of nitrification inhibitors, slow-release fertilisers, and low emission application techniques

4. Ensuring that new technologies around enhanced fuel efficiency and alternative fuel technologies become commercially viable to make an accelerated transition to lower emissions machinery.

5. Investing in renewable fuel sources, such as biomass boilers or anaerobic digestion facilities to maintain optimal growing systems in protected horticultural systems.

6. Optimising energy efficiency of facilities where electricity is used for storing or cooling of fruit and vegetables, and looking at meeting demand with on-site renewables.

7. Minimising the amount of plastic used for mulches, covering polytunnels and packaging, by switching to lower climate impact materials.

In order to enhance carbon removals on farm, four recommendations for areas to focus on are:

1. Increasing soil organic carbon inputs across all productive fields through use of organic amendments such as cover crops, composts and livestock manures. The level of soil carbon building will depend on current levels of saturation, soil type and management practices but regardless will improve nutrient availability to the crop, increase ease of cultivation and potentially improve yields, which will all positively impact emissions.

2. Reducing loss of soil organic carbon by minimising tillage depth. This won't be possible across all crop productions systems, but where viable it will help increase carbon captured in the surface layers of soils.

3. Increasing vegetative (above ground) carbon through increasing length, breadth and height of existing hedgerows, including filling gaps and replanting where hedgerows have died or been damaged. This also includes planting trees in field boundaries, marginal land areas and potentially including trees within the cropping system.

4. Considering how the areas surrounding glasshouses are managed to determine if changes in management could increase carbon removal, where options for sequestration is limited in the production system.

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