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Department for Environment Food & Rural Affairs

Evidence Project Final Report

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Project identification

1. Defra Project code: SCF0129
2. Project title: Harmonisation of Carbon Accounting Tools for Agriculture
3. Contractor organisation(s): RSK ADAS Limited
4. Total Defra project costs (agreed fixed price): £ 99,463.75
5. Project: start date .... November 2021

   end date .... June 2023

6. It is Defra's intention to publish this form.

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Introduction

The UK agricultural sector, and associated food and drink industry, have recognised their role within the low carbon transition and are starting to act. A key starting point is to understand where the current sources of emissions are so that targeted action can be taken to mitigate these. This is done through an assessment of greenhouse gas (GHG) emissions and carbon removals (also called a carbon footprint, carbon audit or carbon assessment; carbon assessment has been used throughout this report). There are different types of assessment that can be completed with corporate organisations having typically required product carbon assessments, while more recently there has been increasing interest in farm-level carbon assessments, where emissions as well as removals are considered. This report focuses on farm-level carbon assessments.

There are a number of carbon calculators (also referred to as GHG calculators or tools, and which can be standalone or part of software packages providing other services) that have been developed over the last 20 years to assess emissions from farms (i.e. a farm-level assessment) or agricultural products (i.e. a product-level assessment). During this time there has been a growing evidence base, development of new global and national methodologies, and creation of standardised databases. This has been alongside the development of new agricultural technologies (e.g. nitrification inhibitors) and changes in user requirements (e.g. the increased interest in measuring carbon removals). Since the 2019 Net Zero legislation was launched there has been an increase in demand for calculators and greater scrutiny of the quality of the outputs produced by these calculators. The speed of change in recent years, plus new entrants to the market, means that there are a range of calculators of differing levels of complexity available to the agriculture sector for assessing emissions and removals.

All carbon calculators are models; there is no single correct answer as they are aiming to simplify a complex biological system. However, it is important to understand why there are differences in results between calculators and identify ways to minimise these differences. Harmonisation of calculators aims to ensure greater levels of precision of outputs, while recognising the need to simplify data entry to support the use by non-expert users (e.g., farmers), in order to facilitate the provision of consistent guidance to farmers to support their decarbonisation efforts.

This project was developed to quantify the level of divergence in calculation of farm-level emissions between a selection of the main carbon calculators on the market, understand the causes of this divergence and determine how those differences might impact the user. By its nature it focuses on the differences between calculators and the challenges of providing robust estimations while making the process accessible to non-expert users. However, it is important to recognise that despite these challenges the calculators are all able to provide the farmer with a baseline understanding of emissions and can facilitate the start, and ongoing development, of a decarbonisation process.

This project aims to understand how we can bring about harmonisation of approaches to farm-level carbon assessment. It is not about identification of which calculator is better or worse than others. It is intended that the insights from this analysis will help inform a potential approach that will enable providers to develop their calculators in a way that creates increased comparability of results while still allowing innovation.

Caveats:

- The project reviewed carbon calculators from a non-expert user perspective and considered how that user would enter data into the calculator for their own farm. It therefore focused on data entry and outputs of the calculations themselves, and not on any consultancy support that may be provided by the calculator providers. It is important to recognise that a number of the calculators have associated consultancy packages that can enhance consistency and accuracy of data entry, which overcome some of the challenges discussed in this report.
- The assessments focused on farm-level carbon assessments, not product-level assessments.
- Analysis of the functionality of the calculators was conducted in May 2023 based on the versions that were publicly available at that time. All but one of the calculators assessed have gone through updates during and since data collection.
- Data is presented anonymised to ensure that any charts or data are not taken out of context and assumptions are not made on which calculator is better or worse based on highest or lowest values and to reflect the fact that, where there are outliers in some datasets, some of the calculator owners have already started work to address these, and therefore current versions of the calculators differ from those that were assessed. Despite this, the principles that have been identified to support development of guidance to enhance harmonisation remain valid.
- Emissions were assessed for all 20 farms using the calculators that were able to assess the relevant enterprises; however, carbon removals or stock changes were only assessed for a subset to test specific functionality of the calculators.

Methodology

The approach taken was to create 20 model farms, with two of each of the nine Defra farm types covering cereals, general cropping, horticulture, mixed, pigs, poultry, dairy, grazing livestock (less favoured area) and grazing livestock (lowland), plus two additional farms testing functionality around anaerobic digestion and agroforestry (silvopasture) in dairy systems. As part of the development of the model farms, consideration was given to key features to be tested in the calculators, such as mitigation practices that are already being used or in development (e.g. methane inhibitors for cattle, nitrification inhibitors for nitrogen fertilisers).

A review was completed of the key calculators available in the UK agricultural sector. From this, a prioritised list of the most widely used or relevant calculators were identified for inclusion in the project and permission was sought from the calculator owners for inclusion in the assessment. The calculators were Agrecalc Ltd's *Agrecalc*, The Cool Farm Alliance's *Cool Farm Tool* (note that this is a product-level carbon calculator and for some model farms multiple product-level footprints were aggregated to give farm-level emissions), Eggbase Ltd's carbon footprint tool, Farm Carbon Toolkit's *Farm Carbon Calculator*, Trinity AgTech's Natural Capital Navigator *Sandy*, and Solagro's *The Farm Carbon Calculator*. The 20 model farms were each run through the calculators that were suitable for that model farm's enterprises. The results were then reviewed to consider how they were affected by the system boundaries, data entry factors, the emission factors, calculations and assumptions, land-based carbon removals and emissions, and support for mitigation.

The results are presented as carbon dioxide equivalent (CO_2e). For farm-level carbon assessments, there are three main greenhouse gases to consider: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These differ in the extent of their impact on global warming. The impact of each is defined relative to carbon dioxide and is referred to as its Global Warming Potential (GWP). Carbon dioxide has a GWP value of 1, methane from non-fossil sources has a GWP value of 27, and nitrous oxide has a GWP value of 273 (according to IPCC's AR6 report). The carbon dioxide equivalent aggregates all greenhouse gases and provides this number in the equivalent amount of carbon dioxide according to their GWPs.

Results

Key findings

The carbon calculators all provided the user with the ability to enter farm-level data and produce a useful output that can support emissions reduction on-farm. However, at the time of assessment, the calculators were materially different in the standards and protocols to which they aligned, their coverage of different enterprises, and their transparency, rigour, consistency and functionality. This resulted in there being a high level of variation in the outputs produced by the different calculators for some of the model farms.

For the two poultry model farms, the highest emissions outputs (without carbon stock changes) were found to be over 350% of the lowest (where 100% means they give the same emissions); this contrasts with the LFA grazing 2 farm where the highest emissions output was only 109% of the lowest emissions output. For seven of the 20 model farms, the highest emissions were more than twice as high as the lowest emissions. The greatest divergence in emissions were seen in farms with organic soils, farms where high levels of soya feed was used (e.g. the poultry systems), and lowland livestock (beef and sheep) farms. The dairy farms results were much more similar between calculators, with the highest emissions output only 123-143% of the lowest; though there were these similarities in overall emissions, the relative contribution of the individual emission sources (e.g. enteric, embedded emissions in feed) could be quite variable between calculators. Where carbon stock changes were included, divergence increased; for one farm on cultivated peat, the highest net emissions output was 171% of the lowest net emissions output when excluding carbon stock change, but this increased to 1,093% when including carbon stock changes.

There was no consistent ranking of the emissions between the calculators across all the farms. Some trends were seen within a farm type (e.g. one calculator gave much higher emissions than the other calculators for both poultry farms), but due to the multiple sources of divergence between the calculators there was not a calculator that consistently gave the highest or lowest emissions when looking across different production systems.

There was a high level of divergence in carbon calculation between the calculators (Table 1), with greater divergence recorded when carbon stock changes were included (for the subset of farms assessed). Alongside a comparison of overall emissions, the analysis also considered the contribution of different emission sources for each calculator. This revealed the key drivers of differences between the calculators (Table 2). For some model farms, this high level of divergence was due to a single outlier result, with the other calculators more aligned in their outputs. For example, emissions in General Cropping 1 had a 171% difference between the smallest and largest outputs (when not including carbon stock change), but this was only 116% when removing results from the calculator with the largest output, suggesting a single factor was driving most of the variation. For other model farms, there was a wide spread of outputs with little alignment between any of the calculators. In some cases this was due to a single factor (e.g. for the poultry assessments, the feed emissions were highly variable between the calculators) or multiple factors (e.g. for the lowland grazing farms there was high levels of variation between the calculators in their enteric, manure management, nitrous oxide soil emissions and embedded feed emissions). There were situations where a number of calculators gave similar levels of overall emissions but differed in the relative contribution of each emission source, which suggests that the similarity in overall emissions was through chance rather than because a harmonised approach was being used. The approach to carbon stock changes was highly variable between calculators, causing further increases in divergence in the net emissions between the calculators. This was particularly so for General Cropping 1, which was on a lowland peat soil, as not all calculators captured emissions from cultivated peat.

The four dairy assessments showed a high level of consistency in results, while there is greater divergence in results across the other sectors. A lack of clear guidance in recent years for calculation of carbon removals or stock changes has meant that the level of divergence in approaches taken here was even greater, with on occasion one calculator implying a removal while another implied an emission even though they were considering the same set of practices. Provision of clearer, agriculture-specific guidance on measurement and reporting of removals would support increased harmonisation of carbon stock change results.

Table 1. Statistics on the farm-level emissions of the 20 model farms. Emissions of max. relative to min. shows the emissions of the calculator with the highest emissions relative to the emissions of the calculator with the lowest emissions (a result of 100% means they give the same emissions). Bold text shows model farms where the maximum emissions were more than twice as high as the minimum emissions. Italic text shows model farms where maximum emissions are less than 150% of the minimum emissions Three model farms also have results that include carbon stock changes (noted by 'w/C stock change'). Here, emissions refer to net emissions where carbon stock changes are included.

Model farm	No. of results	Min. farm emissions (t CO_2e/farm)	Max. farm emissions (t CO_2e/farm)	Mean farm emissions (t CO_2e/farm)	Emissions of max. relative to min.
Cereals 1	5	1,187	2,080	1,636	175%
w/C stock change	5	1,015	2,233	1,661	**220%**
Cereals 2	4	742	949	820	*128%*
Gen. crop. 1	5	281	480	336	171%
w/C stock change	5	297	3,242	1,245	**1,093%**
Gen. crop. 2	4	4	5	4	*129%*
Horticulture 1	3	133	210	174	157%
Horticulture 2	3	1,112	2,650	1,994	**238%**
Pigs 1	4	598	798	716	*133%*
Pigs 2	4	1,539	3,844	2,758	**250%**
Poultry 1	6	78	278	160	**355%**
Poultry 2	5	895	4,014	1,863	**448%**
Dairy 1	5	5,102	6,571	6,022	*129%*
w/C stock change	5	5,132	7,974	6,095	155%
Dairy 2	4	1,442	1,772	1,611	*123%*
Dairy 3	4	4,143	5,858	5,318	*141%*
Dairy 4	4	1,562	2,240	1,862	*143%*
LFA grazing 1	4	2,096	4,115	2,716	196%
LFA grazing 2	4	253	276	268	*109%*
Lowland 1	4	354	996	553	**281%**
Lowland 2	4	141	335	204	**238%**
Mixed 1	4	553	993	755	179%
Mixed 2	4	536	1,164	836	**217%**

Table 2. Key sources of divergence in emissions between the calculators.

Source of emissions	Areas of divergence
Carbon stock changes	Calculators differed in what carbon stock changes were considered in the system boundaries and had different approaches to assessing the carbon stock changes.
Crop residues	Calculators varied in how they account for crop residues remaining on the field leading to differences in how much nitrogen was assumed to be lost as nitrous oxide.
Enteric emissions	There were differences in how the calculators accounted for livestock numbers, activity and feed resulting in variable methane emissions.
Feed embedded emissions	Use of the Global Feed LCA Institute (GFLI) database of emission factors for feed provides some standardisation, but not all were using this. Approach to inclusion of land-use change emissions was variable - especially in soya.
Fertiliser embedded emissions	No consistent set of emission factors were used; use of older factors resulted in higher emissions.
Manure management	Calculators differed in how they account for manure quantity and management practices; some had greater user ability to define what happens to the manures.
Nitrous oxide emissions from fertiliser application	Calculators used a range of methods with varying precision and different emission factors, some of which were internationally applicable whereas others were specific to the UK.

The factors driving the differences between the calculators

- ***System boundaries*** – The calculators apply a range of different system boundaries in the assessment of farm-level emissions. They also differ in terms of the enterprises which can be covered. Some are prescriptive on the system boundaries while others allow the user to determine what to include. There is limited sector-specific guidance available, e.g. The International Dairy Federation have sector-specific guidance for milk production, but for the other sectors more generic carbon reporting standards are used, such as GHG Protocol standards and ISOs 14064 and 14067 to define what should and should not be included.
    a. Users may not understand what they are wanting to assess (e.g. is it a farming enterprise, farm business, or whole estate) and therefore lack clarity on whether they should include aspects outside of the farming operations, such as diversification or forestry within an assessment.
    b. Calculators differed in what the user could include within the system boundaries. This allows a flexible approach to what farms assess depending on their organisational structures, but also creates inconsistencies when looking to compare farm-level assessments.
    c. Calculators differed in the level of guidance provided to users in how to select what was included in the system boundary when aligning to a particular standard. Approaches taken ranged from no guidance, guidance within the calculator itself, through to provision of consultancy support.
- ***Data entry factors*** – A major driver of the choices made by calculator developers has been balancing the amount of data that users need to provide against the extent of assumptions that the calculator must make. Increased granularity of data enables greater understanding of emissions and insight into where mitigation actions would provide benefits but does increase the burden on users to collect more granular data and spend time entering it. Where more complex data entry is used, calculators have a range of options to support users in increasing accuracy of data collection. These range from simple help pop-ups on screen, automated validation processes, through to more sophisticated machine learning and artificial intelligence approaches.
- ***Emission factors –*** Standardised datasets for UK energy emission factors (i.e. the UK Government Conversion Factors) are available and widely used in the UK-specific calculators. The Global Feed LCA Initiative (GFLI) have worked to develop a standardised set of emissions factors for feed products. *Fertilizers Europe* provide emission factors for many of the key fertilisers used in the UK that are produced in Europe, and some comparisons to those produced elsewhere. However, not all the calculators used these data sources, and where this was the case, this resulted in some large differences in emissions between calculators. Greater alignment to standard databases will support increased harmonisation. There were some calculators that were providing actual emission factors for specific feeds or fertilisers directly from the manufacturers; where this is the case, it is important that the manufacturers use robust data collection approaches.

- ***Calculations and assumptions*** – The IPCC guidelines form the foundation of the agricultural emissions assessment for methane and nitrous oxide. The IPCC 2006 guidelines formed the baseline calculations for earlier calculators, but in 2019 there was an update to the guidelines and emission factors. Only some calculators are fully aligned with the 2019 guidelines; harmonisation of methodologies will be enhanced once all calculators move to using the latest IPCC factors. However, within the IPCC guidelines there are Tier I, Tier II and Tier III approaches and emission factors, which creates divergence due to how spatially explicit and sensitive to different systems and management each calculator's assessments are. Some calculators aim to provide a globally-aligned approach while others are UK-specific.
- ***Land-based carbon removals and emissions*** – There was no single consistent approach taken to assess carbon removals or emissions from soils, vegetation and land use change within the calculators, reflecting a lack of clear and consistent guidance in this area. Standards, such as the draft GHG Protocol Land Sector and Removals guidance, aim to provide global guidance, while ISO 14064:2 provides generic guidance on sequestration and accounting for permanence, but neither are specifically aimed at farm-level carbon accounting. One approach taken in a number of the calculators was the alignment with the IPCC Tier I methodology for carbon stock change in mineral soils; however, this approach is not designed to assess sequestration at farm scale and rarely were sufficient questions asked to understand permanence, additionality and leakage. One calculator has developed a more sophisticated approach to carbon removals that combined modelling alongside physical measurements at the time of this study. In order to be able to account for a removal against this standard there is a requirement to provide quantitative uncertainty estimates, which was observed in only one of the calculators at the time of the assessment. This is an evolving area in the calculators and the standards, and therefore it is important that users are made explicitly aware of uncertainties associated with the approach. Where *carbon stock changes* have been presented rather than *carbon sequestration/removals* this should be made explicit.
- ***Quantification of mitigation*** – The ability to include emission mitigation practices or technologies and quantify their impact within the calculator (e.g. nitrification inhibitors used with nitrogen fertilisers) helps guide users to practices that provide emission-reduction benefits to their farms and captures the impact of those actions in the output, incentivising their uptake. Tier I methodologies are limited in their ability to meaningfully include many mitigation practices. Incorporation of new technologies within the calculators also allows the user to understand what impact they might have before they make costly investments. The calculators differed in the technologies and level of detail for mitigation practices that they were able to include. Alongside the inclusion of mitigation practices within the calculator, some calculators are showing increasing levels of sophistication in supporting the user to understand what mitigation opportunities are available to them.

Key conclusions

In order to support farm-level carbon assessment as part of the continuous process of decarbonisation, it is important that farmers and the supply chain have confidence in the approach and understand what it is delivering. The current level of divergence in carbon assessment between calculators can be extensive. Addressing this through a focus on the use of latest standards and protocols, full representation of a farm's activities, guidance on emissions and removals, increasing functionality through greater data granularity, and maintenance of up-to-date emission factors will increase user and industry confidence and increase relevance to the user's farm.

When aiming to harmonise farm-level carbon assessment, it is important to define first why an assessment is being made, what it is trying to measure, and who the output is for. It is recommended that there is a clear agreement developed within the industry as to why farmers should be completing farm-level emissions assessments (as opposed to individual product-level assessments), in order to create clear guidance of what should and should not be included.

Increased harmonisation of carbon calculator results would be supported by the provision of sector- and enterprise-specific guidance that is aligned with the approaches taken in generic guidance and standards, such as those provided by GHG Protocol, Science Based Targets initiative and ISO. Alongside supporting greater clarity of what is meant by a farm-level carbon assessment, this guidance should provide general recommendations for the agricultural sector, such as recommendations on what emission factor databases to use, while enterprise-specific guidance can address specific challenges, such as how to deal with embedded emissions from purchased livestock. Improved guidance on a standardised approach to assessing and quantifying carbon removals in soils, vegetation and from land use changes will support greater harmonisation of approaches in calculators around carbon removals. This should, for example, include a requirement to include emissions from peat soils. It is important that guidance includes requirements for the level of rigour and evidence needed to support removals claims, reflecting the importance of permanence, additionality, saturation and leakage in understanding of removals along with estimates of uncertainty.

The methodologies and emission factors used in carbon accounting are being refined and updated, and new technologies to mitigate climate change impacts are being developed. Carbon calculators need to be able to review and update to be aligned with the latest science and research, but need to have a transparent approach to communicating with users how they are aligning, the frequency of updates and the current stage of alignment.

Greater granularity of input data was found in the analysis to lead to greater responsiveness of the calculator outputs to changes in practice. For example, greater detail of feed allocation to cattle meant that enteric methane calculations were more responsive to dietary changes. Where data was collected at herd level there was less evidence of results changing in response to data entry. Therefore, it is recommended that calculators aim to allow greater granularity of data entry in areas where the largest emissions are seen, while simplifying data entry in areas where climate impact is less significant (in cases where simplification is a user requirement).

Even with guidelines to bring about harmonisation, some difference is likely to always remain between calculators. These do not necessarily reflect the accuracy of the calculators but can instead result from the calculators having to make assumptions to model these complex systems and because the calculators differ in the functionality that they provide. It will be important to support users to identify the calculator that provides the right level of standards, functionality and precision for their needs and enable them to generate data that can drive practical actions for reducing emissions and increasing removals. Alongside this, it is important to recognise that the more informed the user is, the more value and accuracy they will gain from a farm-level carbon assessment, and therefore there remains a need for knowledge transfer to upskill the industry to understand how to decarbonise and improve their understanding of carbon accounting.

Recommendations

Our recommendations for supporting the harmonisation of farm-level carbon accounting are:

1. Industry and HMG to clearly define what a farm-level assessment is, how it is going to be used, and what parts of a farm business should and should not be included.
2. Calculators to align with the requirements of the latest standards and guidance – currently GHG Protocol standards (including the upcoming Land Sector and Removals guidance), ISO 14064 and ISO 14067. Industry and HMG to provide guidelines to support a standardized way of applying these in an agricultural context.
3. Calculator providers to regularly review and update calculators to account for changes in scientific knowledge, carbon accounting methodologies and new emission factors.
4. Calculators to comply with the latest IPCC guidance (currently IPCC 2019) and use those calculations and emission factors as defaults where Tier I approaches are used. Where appropriate, calculators to use Tier II and Tier III calculations where robust emission factors and methodologies are available, such as emission factors created for the UK GHG Inventory.
5. Calculators to use emission factors from an agreed set of robust databases for embedded emissions in fertilisers, feeds and fuels. Industry to support the development of appropriate emission factors for embedded emissions in purchased livestock.
6. Calculators to present outputs in compliance with the latest standards. Industry and HMG to define consistent disaggregated output categories for use by all calculators to facilitate understanding of emission sources.
7. Calculator providers to build user confidence through transparency of approach and third-party verification of the alignment of calculators to minimum standards.

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
    - the objectives as set out in the contract;
    - the extent to which the objectives set out in the contract have been met;
    - details of methods used and the results obtained, including statistical analysis (if appropriate);
    - a discussion of the results and their reliability;
    - the main implications of the findings;
    - possible future work; and
    - any action resulting from the research (e.g. IP, Knowledge Exchange).

Introduction

The UK agricultural sector, and associated food and drink industry, have recognised their role within the low carbon transition and are starting to act. A key starting point is to understand where the current sources of emissions are so that targeted action can be taken to mitigate these. This is done through an assessment of greenhouse gas (GHG) emissions and carbon removals (also called a carbon footprint, carbon audit or carbon assessment; carbon assessment has been used throughout this report). There are different types of assessment that can be completed with corporate organisations having typically required product carbon assessments, while more recently there has been increasing interest in farm-level carbon assessments, where emissions as well as removals are considered. This report focuses on farm-level carbon assessments.

There are three main greenhouse gases that are important in agricultural carbon assessment – methane, nitrous oxide and carbon dioxide. Each gas has a different level of impact on global warming. This is captured in its Global Warming Potential (GWP), which is a measure of the amount of thermal energy it absorbs relative to the reference gas, carbon dioxide. According to the latest IPCC report (AR6), carbon dioxide has a GWP value of 1, methane from non-fossil sources has a GWP value of 27, and nitrous oxide has a GWP value of 273 (Forster et al., 2021).

Methane (CH_4) emissions are predominantly associated with the anaerobic (without oxygen) breakdown of organic material, either as part of the digestion process (particularly in the rumen of cattle and sheep – referred to as enteric fermentation) or in manure storage. Methane is a natural part of the carbon cycle and once released into the atmosphere, although it has a high global warming potential at release, will break down into carbon dioxide and water after 10-20 years. The level of methane produced in a system is dependent on a number of interlinking factors such as the type of diet, digestibility of diet and type of livestock, or how manure is managed from housing through to application.

Nitrous oxide (N_2O) is released both directly on-farm and indirectly following the release of ammonia (via volatilisation) to the air or loss of nitrate (via leaching) into water and then deposition outside of the farming system. The nitrous oxide emissions result from the application of nitrogen sources, such as manufactured nitrogen fertilisers, organic manures, crop residues, leguminous crops (which are capable of fixing atmospheric nitrogen into nitrogen sources that plants can use) and other organic materials to the soil and the interaction of that nitrogen with soil microbial organisms. There are a range of different factors that affect nitrous oxide release, such as quantity of nitrogen applied, timing of application, temperature and moisture at application, nitrogen uptake by the crop, and soil type. The complexities of these emissions sources mean that it is not practical to directly measure emissions on-farm; instead approaches have been developed to model these emissions, based on experimental evidence, to help support targeted action in reducing impact.

Carbon dioxide (CO_2) emissions mainly relate to the burning of fossil fuels. Due to its low GWP relative to nitrous oxide and methane, carbon dioxide contributes a relatively small part to the overall climate impact of agriculture. However, embedded emissions from production of manufactured fertiliser, which are predominantly CO_2, are an important contributor to many crop assessments. Carbon dioxide emissions can also result from the oxidation of stored carbon (e.g. the breakdown of soil organic matter). Conversely, carbon sequestration, where carbon stocks are being enhanced, results in the removal of carbon dioxide from the atmosphere.

Carbon dioxide equivalent (CO_2e) is a way of aggregating different greenhouse gases by weighting their contribution based on their GWP. The emissions presented in this report are given in CO_2e. In addition, the embedded emissions from feed and other purchased items are reported in CO_2e in most assessments even though the actual emissions for many feeds will be predominantly nitrous oxide. Where land use change occurs resulting in the loss of soil carbon or carbon in vegetation this will also be reported as CO_2e.

Reporting of emissions and removals can occur at different levels. There is a well-established reporting process for national-level emissions via the National Atmospheric Emissions Inventory (NAEI). The agriculture part of the inventory focuses on those emissions that occur on-farm and uses farm practice data from across the country to assess emissions for the whole of the farming sector. The agriculture part of the inventory is combined with other sectors to allow UK-level reporting of all GHG emissions, including transport and industrial processes used to create manufactured fertilisers. In addition, soil carbon and biomass stock changes are reported separately in the land use, land use change and forestry (LULUCF) section of the inventory.

Although the national-level assessment provides a good understanding of changes in calculated GHG emissions over time (without taking carbon removals into consideration), at the agricultural-industry level, it is important to have a greater level of granularity to target actions and understand what is happening at farm level, and understand how emissions from sectors contributing farm inputs (the embedded emissions) impact the farm. There are a number of different reasons for assessing emissions and, increasingly, carbon removals (sequestration) from agricultural systems. These can range from high-level assessments to help farmers understand where key sources are to provide a starting point for delivering changes in practice to reduce emissions, through to farmers wanting to be proactive in developing a mitigation strategy for themselves, to those assessments that are being completed as part of supply chain programmes – here they may be being used to support changes in practice, but increasingly they are also being used to support Scope 3 emissions reporting often as part of corporate SBTi (Science-Based Targets initiative) reporting. For farmers, a whole farm-level accounting process might be required to understand all activities on-farm, whilst in supply chain accounting there may be a focus on a specific enterprise or product that the farm produces.

In order to calculate emissions from agricultural systems, guidance and assessment methodologies are required. The high-level guidance and methodological development for emissions assessment and carbon removals at a national level is provided by the Intergovernmental Panel on Climate Change (IPCC). It also provides default emission factors to use for some aspects of farm-level calculations. This guidance is used in the creation of the UK GHG Inventory. The main guidance was drafted in 2006, with an update provided in 2019 that refines many of the emission factors and models and adds additional details to the assessment process. However, this guidance is developed for national-level reporting and therefore has to be interpreted and adapted for use at farm scale.

There have been a number of standards developed over the years that can be used for assessing emissions from agricultural products and farms. These include the PAS 2050:2011 Specification for the assessment of the life cycle emissions from goods and services, Greenhouse Gas Protocol standards (Product Life Cycle, Corporate, Corporate [scope 3] value chain and the draft Land Sector and Removals Guidance), and ISO 14064 & ISO 14067 (providing guidance for creating carbon footprints at the organisation level and product level, respectively). In addition, the corporate world is starting to align itself with the need to reduce GHG emissions and capture carbon removals robustly; therefore more and more organisations are signing up to the Science Based Targets initiative to set robust targets for emissions reductions. Farmers typically manage large carbon stocks in soils and biomass; therefore, emissions and removals of carbon stock are particularly important to account for. It is important to note that while all the other standards mentioned above require that emissions and removals related to carbon stock loss or gain should be included in assessments if significant to the system being assessed, the now outdated PAS 2050 standard says that they must be excluded unless resulting from land use change. There are other standards that have relevance to farm-level carbon assessments. For example, both ISO 14068 and PAS 2060 provide support for demonstrating carbon neutrality while BS 8632:2021 provides guidance on natural capital accounting. For calculators to be able provide outputs for certain markets (e.g. carbon credits, product ecolabelling), there will be a requirement to comply with specific standards. For example, the Carbon Trust's product carbon footprint labels require compliance with the ISO standards where previously it required compliance with the PAS standards.

There are a number of carbon calculators (also referred to as GHG calculators or tools, and which can be standalone or part of software packages providing other services) that have been developed over the last 20 years to assess emissions from farms (i.e. a farm-level assessment) or agricultural products (i.e. a product-level assessment). During this time there has been a growing evidence base, development of new global and national methodologies, and creation of standardised databases. This has been alongside the development of new agricultural technologies (e.g. nitrification inhibitors) and changes in user requirements (e.g. the increased interest in measuring carbon removals). Since the 2019 Net Zero legislation was launched there has been an increase in demand for calculators and greater scrutiny of the quality of the outputs produced by these calculators. The speed of change in recent years, plus new entrants to the market, means that there are a range of calculators of differing levels of complexity available to the agriculture sector for assessing emissions and removals.

All carbon calculators are models; there is no single correct answer as they are aiming to simplify a complex biological system. However, it is important to understand why there are differences in results and identify ways to minimise these differences. Harmonisation of calculators aims to ensure greater levels of precision of outputs, while recognising the need to simplify data entry to support the use by non-expert users (e.g. farmers), in order to facilitate the provision of consistent guidance to farmers to support their decarbonisation efforts.

This project was developed to quantify the level of divergence in calculation of farm-level emissions between a selection of the main carbon calculators on the market, understand the causes of this divergence and determine how those differences might impact the user. By its nature, the report focuses on the differences between calculators and the challenges of providing robust estimations while making the process accessible to non-expert users. However, it is important to recognise that despite these challenges the calculators are all able to provide the farmer with a baseline understanding of emissions and can facilitate the start of a decarbonisation process and support ongoing continuous improvement.

This project aims to understand how to bring about harmonisation of approaches to farm-level carbon assessment. It is not about identification of which calculator is better or worse than others. It is intended that the insights from this analysis will help inform a potential approach that will enable providers to develop their calculators in a way that creates increased harmonisation of results while still allowing innovation.

Caveats:

- The project reviewed carbon calculators from a non-expert user perspective and considered how that user would enter data into the calculator for their own farm. It therefore focused on data entry and outputs of the calculations themselves, and not on any consultancy support that may be provided by the calculator providers. It is important to recognise that a number of the calculators have associated consultancy packages that can enhance consistency and accuracy of data entry, which overcome some of the challenges discussed in this report.
- The assessments focused on farm-level carbon assessments, not product-level assessments.
- Analysis of the functionality of the calculators was conducted in May 2023 based on the versions that were publicly available at that time. All but one of the calculators assessed have gone through updates during and since data collection.
- Data is presented anonymised to ensure that any charts or data are not taken out of context and assumptions are not made on which calculator is better or worse based on highest or lowest values and to reflect the fact that, where there are outliers in some datasets, some of the calculator owners have already started work to address these, and therefore current versions of the calculators differ from those that were assessed. Despite this, the principles that have been identified, to support development of guidance to enhance harmonisation remain valid.
- Emissions were assessed for all 20 farms using the calculators that were able to assess the relevant enterprises; however, carbon removals or stock changes were only assessed for a subset to test specific functionality of the calculators.

Key terminology

- **Carbon assessment** (also referred to as carbon footprints or audits, GHG emission assessment) – this is an assessment of the GHG emissions and carbon removals from a farm, enterprise or product, calculated using a combination of activity data and emission factors (and associated equations) and presented as carbon dioxide equivalents.
- **Carbon calculator** (also referred to as calculators or software systems) – a simple or complex modelling system that allows the user to enter activity data from the farm, enterprise or product and provides a combination of calculation methodologies and emission factors to convert the activity data into a value that represents the emissions produced as a result of that activity.
- **Farm-level carbon assessment:** GHG emissions inventories of all inputs, operations and outputs within the boundaries of the farm business across all enterprises. However, the boundary and definition of what a ‘farm’ is remains uncertain as these can be complex enterprises with both farming and non-farming activities taking place, using potentially shared resources.
- **Enterprise-level carbon assessment:** GHG emissions inventories that itemize the emissions from all of the operations that together comprise the reporting company enterprise (e.g. a dairy unit).
- **Product-level carbon assessment:** GHG emissions inventories of the entire life cycle impacts of individual products or services, from raw material extraction to product disposal.
- **Carbon stock change:** change (i.e. increase or decrease) in the amount of carbon stored in a particular ecosystem (e.g. the soil carbon stock).
- **Carbon sequestration:** the permanent net transfer of CO_2 from the atmosphere to the land where it is stored in soils and vegetation. A carbon sink is a system that is absorbing and storing, for an indefinite period, more carbon from the atmosphere than it is releasing.
- **Scopes:** Emissions are categorised into three Scopes. For a farm, Scope 1 emissions are those under the direct control of the farm (e.g. emissions from using fossil fuels, nitrous oxide emissions from fertiliser application, and methane emissions from livestock and manures); Scope 2 emissions are indirect emissions from the production of energy that the farm purchases (e.g. electricity from the National Grid); and Scope 3 cover emissions from the value chain that are not under direct control of the farm (e.g. embedded emissions in purchased fertiliser and feed, emissions associated with waste disposal).
- **Tiers:** Emission calculations are divided into three Tiers based on their complexity and specificity. For a farm, Tier I calculations are simple methods using default emission factors (e.g. global emission factors); Tier II calculations take into account local activity data (e.g. country-specific emission factors); and Tier III calculations are modelling approaches that take into account farm-specific conditions (e.g. a model that accounts for soil type, weather conditions and management practices).

Methodology

Overview
The approach adopted in this project was to calculate greenhouse gas emissions using a range of commonly-used carbon calculators for 20 model farms representing the main farming systems in operation across England and Wales. The results were then evaluated to determine where there were differences and the cause of those differences, whether from data entry, emission factors, methodology or other associated factors.

Selection of model farms
There were 20 model farms that were created for this project these are summarised in Table 3. The case studies were chosen so as to have two farms from each of the nine Defra standard farm types (cereals, general cropping, horticulture, mixed, specialist pigs, specialist poultry, dairy, grazing livestock (least favoured areas) and grazing livestock (lowland), plus two additional test cases that included additional features to test in the calculators. For each model farm, we aimed to test key functionality in the calculators, ranging from simple checks of whether the calculator works for the farm system (e.g. poultry, protected horticulture, perennial crops) through to more complex checks such as whether there is sufficient functionality to understand the impacts of adopting certain mitigation practices, or changes in farming practices, such as adoption of agroforestry. Note that these model farms are highly variable in scale and output so the results cannot be used to draw conclusions on how the scale of emissions vary between different enterprises.

Table 3. Brief summary of the 20 model farm types selected for use in this analysis.

Farm Type	Intensive system (1)	Lower intensity system (2)
Cereals	Intensive cultivation – rotational ploughing; Rotation cereal, cereal, break crop (OSR or beans); Soil type: Heavy clay. Area of woodland.	Regenerative – minimum tillage; Organic manures; Soil type: chalky downland
General cropping	Conventional potato production; Soil type: Fenland peat	Organic vegetable production; Soil type: Light sandy soil
Horticulture	Glasshouse tomato production; Hydroponic production	Orchard cider apples; Soil type: Loam
Specialist pigs	Indoor rearing; All feed bought in	Outdoor breeding; Some wheat grown; Soil type: Silt
Specialist poultry	Indoor broilers; for the purpose of this assessment, the farm is assumed to not include any vegetation	Free range layers; Tree/hedgerow cover in ranging area
Dairy	Intensive, fully-housed cattle (slurry); Bought in soya-based ration; Calves reared off-site. Area of woodland.	Extensive, largely outdoor grazing; Grass-based system with minimal additional feed; In-house calf rearing; Soil type: Clay and silt
Other (dairy)	Dairy with anaerobic digester - manures only. Advanced system using inhibitors, etc.	Dairy with agroforestry.
LFA grazing	Upland beef and sheep; Home cut silage; Winter feed, indoor lambing	Hill sheep; Peatland; Outdoor lambing
Lowland grazing	Intensive, housed beef finishing – FYM; Grain/soya-based diet; Animals bought onto the farm and finished; Soil type: Clay	Suckler beef, largely grazed, herbal leys, cover crops; Outwintered on bales; Soil type: Sandy soil
Mixed	Cereals and beef/sheep; use of farmyard manure on crop area	Cereals and dairy; use of slurry on crop area

Selection of carbon calculators
An initial review of carbon calculators identified 81 calculators available for use on-farm from across the world. A short list was created based on relevance to UK agriculture, accessibility, uptake within the sector, and availability of supporting resources for the evaluation process; this reduced the list down to ten that

were relevant to farming systems in England and Wales. Of these there were five that the project team were able to gain access to. An additional calculator was identified for use in poultry to provide additional specialist assessments. In total six carbon calculators were included in the final analysis: Agrecalc Ltd's Agrecalc (assessed prior to the release of the new version, Agrecalc Cloud); The Cool Farm Alliance's *Cool Farm Tool* V2.0 (note that this is a product-level carbon calculator and for some model farms multiple product-level footprints were aggregated); Eggbase's carbon footprint tool (covering poultry enterprises); Farm Carbon Toolkit's *Farm Carbon Calculator* (after May 2023 updates); Trinity Agtech's Natural Capital Navigator, *Sandy* v4.0; and Solagro's *The Farm Carbon Calculator* v3.1 (Excel-based calculator, not updated since 2016). Four of which are free for farmers to use (with some limitations) and two are commercial calculators, which have a cost associated with use.

Data capture and analysis
All 20 farms were run through three of the calculators (Agrecalc, Farm Carbon Calculator and Sandy), all but the horticulture farms were run through Cool Farm Tool (though as of October 2023 the Cool Farm Alliance has recommended not to use the 'Other livestock' module in Cool Farm Tool due to the need for a significant update; this covers poultry, sheep and pigs), the two poultry farms were captured in Eggbase and four farms were run through Solagro (Cereals 1, General Cropping 1, Poultry 1 and Dairy 1; the calculator has the capacity to cover other enterprises, but it was recognised that the calculator had not been adequately updated in a number of years and an assessment of only a subset of farms was chosen). The results were extracted from the different calculators and the differences in emissions were identified for further investigation. Some aspects were evaluated through an analysis of the calculator's guidance documents to understand what emission factors and methodologies were used, whilst other differences were evaluated through the use of simple scenarios to test how changes in specific aspects (e.g. nitrogen source, type of feed, volume of feed) impacted on results to determine how sensitive the calculator was to changes in specific parameters. In addition, discussions were held with the calculator owners to support interpretation of the differences in results to ensure that the project team's evaluation was correct and to identify the key reasons for divergence or convergence. It is important to note that in response to developments in science, carbon accounting methodology and emission factor databases, calculators need to periodically review and update their processes. During the course of this analysis, some of the calculators have undergone major upgrades. Therefore, this report has focused on the functions and features of different approaches and the desired characteristics of calculators that might increase harmonisation, rather than specifically focusing on the results from one calculator versus another. All results presented in this report are based on the versions of the calculators that were available as of May 2023. Throughout the results the carbon calculators are referred by a letter code, A, B, C, D, E and F.

Results

The farm-level GHG emissions are presented for all the model farms. For three farms we also present emissions or removals resulting from decreases or increases in carbon stock. These examples were used to understand the key functionality of the calculators in assessing removals in particular, and identification of sources of divergence.

It is important to note that the highest and lowest values cannot necessarily be considered to be the best or worst calculators as there are a range of different reasons for values being higher or lower, such as what is actually included in the assessment. For example, a more comprehensive assessment is likely to have a higher emission value but may also provide greater functionality to support a user in reducing emissions, whilst a lower value may represent a calculator that is using up-to-date emission factors that reflect decarbonisation within areas such as fertiliser production or electricity generation. Therefore, it is important to not just look at the scale of emission per farm, but to understand the reasons for the differences.

Whilst understanding the differences between extreme output values from the different calculators is important, it is also important to recognise that similarities between the outputs from the different calculators may not reflect that a harmonised approach has been taken by the calculators. There may be methodological differences in how emissions for different source categories are calculated and these might not necessarily be revealed when considering the overall farm-level emissions for the model farms assessed in this report. For reasons described in the following sections, these differences are important to be aware of since they affect not only the accuracy and precision of the calculator outputs, but also the calculators' sensitivity to site and management conditions, and their sensitivity to mitigation options which users want to consider. It is important not to look at the overall level of emissions in isolation, but to also understand what has contributed to those emissions.

These farm-level emissions and detailed breakdowns of emission sources for a subset of the model farms were used to identify where there are divergences between the calculators. The analysis section investigated the cause of these divergences.

A summary of results from all systems are presented in Table 4. The final column shows the percentage of the highest emission relative to the lowest emission. For some model farms, this high level of divergence was due to a single outlier result, with the other calculators more aligned in their outputs. For example, emissions in General Cropping 1 had a 171% difference between the smallest and largest outputs (when not including carbon stock change), but this was only 116% when removing results from the calculator with the largest output, suggesting a single calculator was driving most of the variation. For other model farms, there was a wide spread of outputs with little alignment between any of the calculators. In some cases this was due to a single factor (e.g. for the poultry assessments, the feed emissions were highly variable between the calculators) or multiple factors (e.g. for lowland grazing farms there was high levels of variation between the calculators in their enteric, manure management, nitrous oxide soil emissions and embedded feed emissions). There were a number of calculators that had similar levels of overall emissions but differed in the relative contribution of each emission source, which suggests that the similarity in overall emissions was through chance rather than because a harmonised approach was being used. The approach to carbon stock changes was highly variable between calculators, causing further increases in divergence in the net emissions between the calculators. This was particularly so for General Cropping 1, which was on a lowland peat soil, as not all calculators captured emissions from cultivated peat.

Table 4. Statistics on the farm-level emissions of the 20 model farms. Emissions of max. relative to min. shows the emissions of the calculator with the highest emissions relative to the emissions of the calculator with the lowest emissions (a result of 100% means they give the same emissions). Bold text shows model farms where the maximum emissions were more than twice as high as the minimum emissions. Italic text shows model farms where maximum emissions are less than 50% higher than minimum emissions. Three model farms also have results that include carbon stock changes. Here, emissions refer to net emissions where carbon stock changes are included.

Model farm	No. of results	Min. farm emissions (t CO_2e/farm)	Max. farm emissions (t CO_2e/farm)	Mean farm emissions (t CO_2e/farm)	Emissions of max. relative to min.
Cereals 1	5	1,187	2,080	1,636	175%
w/C stock change	5	1,015	2,233	1,661	**220%**
Cereals 2	4	742	949	820	*128%*
Gen. crop. 1	5	281	480	336	171%
w/C stock change	5	297	3,242	1,245	**1,093%**
Gen. crop. 2	4	4	5	4	*129%*
Horticulture 1	3	133	210	174	157%
Horticulture 2	3	1,112	2,650	1,994	**238%**
Pigs 1	4	598	798	716	*133%*
Pigs 2	4	1,539	3,844	2,758	**250%**
Poultry 1	6	78	278	160	**355%**
Poultry 2	5	895	4,014	1,863	**448%**
Dairy 1	5	5,102	6,571	6,022	*129%*
w/C stock change	5	5,132	7,974	6,095	155%
Dairy 2	4	1,442	1,772	1,611	*123%*
Dairy 3	4	4,143	5,858	5,318	*141%*
Dairy 4	4	1,562	2,240	1,862	*143%*
LFA grazing 1	4	2,096	4,115	2,716	196%
LFA grazing 2	4	253	276	268	*109%*
Lowland 1	4	354	996	553	**281%**
Lowland 2	4	141	335	204	**238%**
Mixed 1	4	553	993	755	179%
Mixed 2	4	536	1,164	836	**217%**

The four dairy assessments showed the greatest consistency in results between the calculators, while there is greater divergence in results across the other sectors. A lack of clear guidance in recent years for calculation of carbon removals or stock changes has meant that the level of divergence in approaches taken here was even greater, with on occasion one calculator implying an overall farm-level removal while another implied an emission even though they were considering the same set of practices. Provision of clearer, agriculture-specific guidance on measurement and reporting of removals would support increased harmonisation of carbon stock change results.

Such differences may affect the accuracy and precision of the calculator outputs, and the calculators' sensitivity to site and management conditions, and their ability to identify and characterise mitigation options effectively.

Note that there have been changes in some of the calculators since data collection and further changes have been planned for some calculators, which will reduce some of this difference. Calculator F has not been updated since 2016 and it is unclear if it will be, so this was excluded from most of the assessments. Excluding it from all assessments would have reduce some of the variation seen.

More detailed results are presented below with a breakdown of emissions for a subset of the model farms. The emission categories used in this report are presented in Table 5.

Table 5. Emission categories

Category	Description of what is included in this category
Carbon stock change	The net change in carbon stored within the farm system (i.e. in soils or vegetation), expressed in terms of losses or gains of CO_2e.
Crop residues	Emissions associated with both direct and indirect nitrous oxide emissions from nitrogen released from crop residues.
Enteric	Emissions resulting from ruminant livestock microbial fermentation.
Feed	Emissions associated with the production of purchased feed.
Fertiliser application	Nitrous oxide emissions from soils after nitrogen fertiliser application. These result from nitrification and denitrification processes by micro-organism activity in the soil. This includes direct emissions, where the nitrous oxide is released in the field of application, and indirect emissions, where the nitrogen is lost from the field via volatilisation or leaching/run off and converted into nitrous oxide away from the field of application.
Fertiliser production	Embedded emissions associated with the production of fertilisers.
Fuel	Emissions related to energy use. This includes Scope 1 emissions (i.e. fossil-fuel use on-farm), Scope 2 emissions (i.e. purchased electricity) and Scope 3 emissions (i.e. emissions associated with *extraction, refining and transportation of fossil fuels* and *transmission and distribution of electricity*).
Manure (and grazing)	Emissions related to production and application of manure as well as those associated with livestock grazing.
Pesticide production	Embedded emissions associated with the production of pesticides.
Other	This captures various emissions that do not fall under the main categories.

Arable and horticultural farms

Farm-level emissions for **arable** and **horticultural** model farms are presented in Figure 1. ***Cereals 1*** had highly variable emissions with the highest emissions for calculators A and F. Emission were similar across the calculators for ***Cereals 2***. ***General Cropping 1*** had much higher emissions for calculator F. ***General Cropping 2*** emissions were similar between calculators. Both ***Horticulture 1*** and ***Horticulture 2*** follow a similar pattern of highest emissions for A and lowest emissions for E.

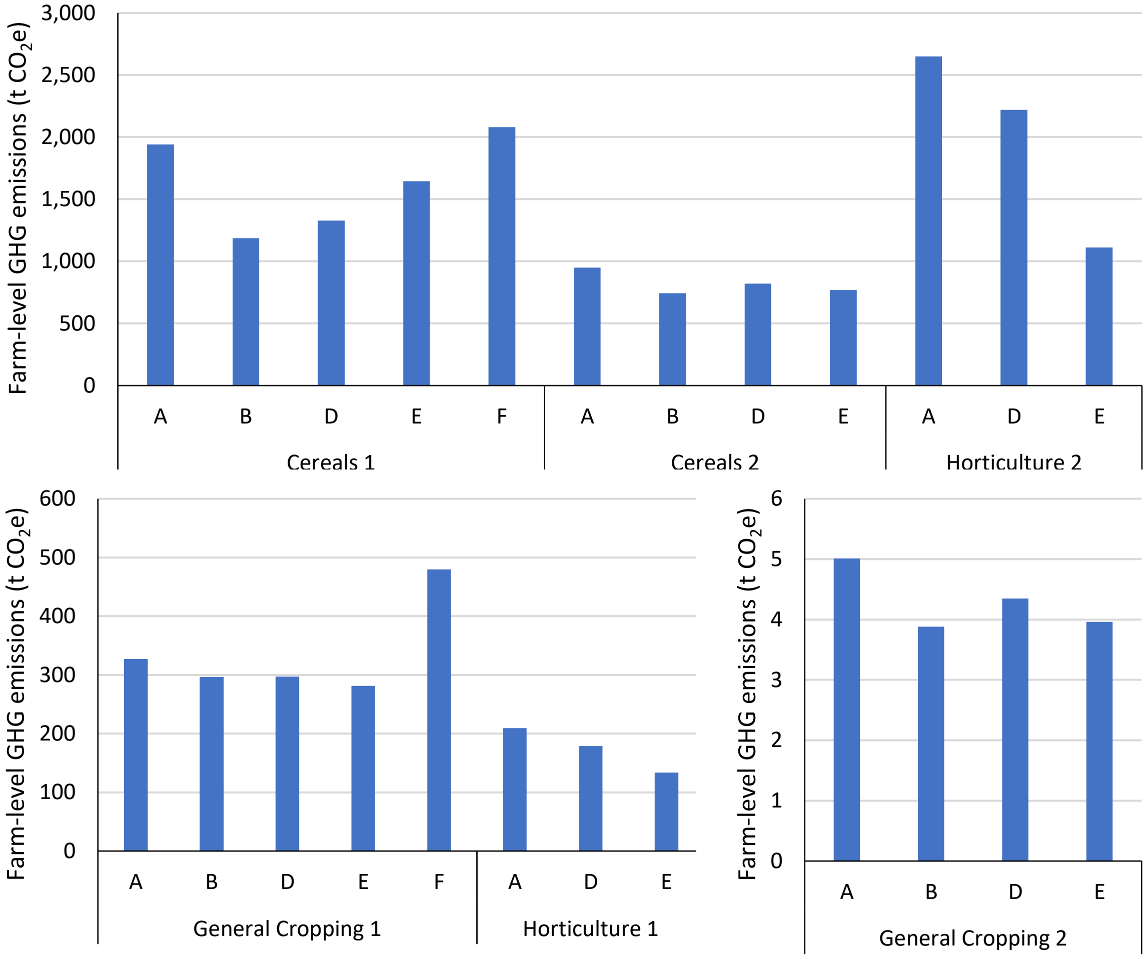


Figure 1. Farm-level emissions for arable and horticultural model farms (without carbon stock change). Presented on three charts due to scale of emissions varying between model farms, reflecting a combination of size and practices.

The farm-level net emissions for ***Cereals 1***, including carbon stock change, are disaggregated into the major emission sources (Figure 2). Note that it was not possible to disaggregate emissions to the same level for all calculators due to how they present their outputs. Calculator D combines *Fertiliser production* and *Fertiliser application* (presented in the figure as *Fertiliser production*) and calculator F combines *Crop residues* within *Fertiliser application*.

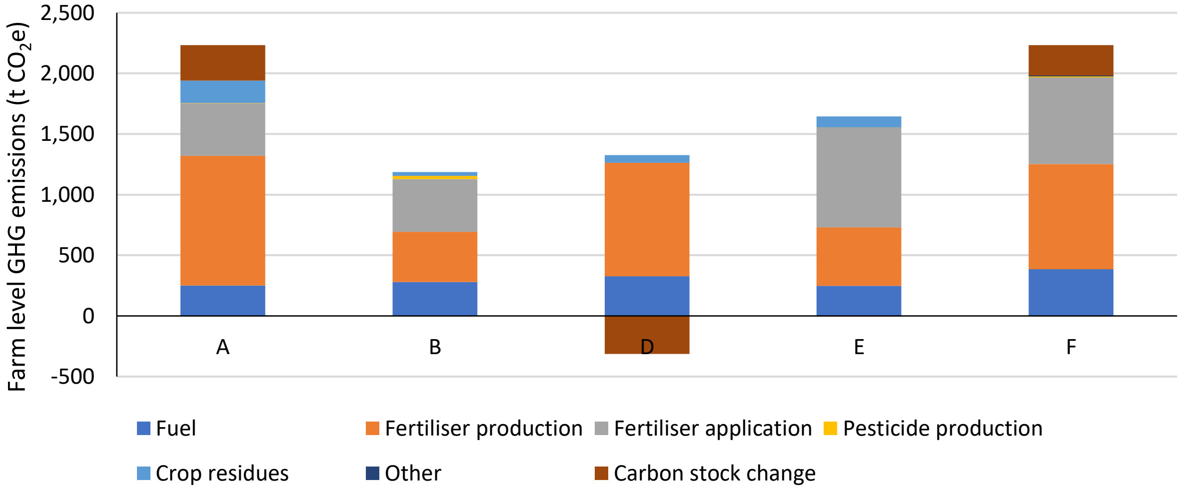


Figure 2. Breakdown of emissions for the Cereals 1 model farm (including carbon stock change).

Fertiliser production was either the largest or second largest source of emissions for all calculators. The lowest emissions related to fertiliser production were observed in B and E (and assumed in D, but lack of disaggregation makes this uncertain). In A and F, fertiliser production emissions were almost double those in the other calculators due to the use of an older source of fertiliser production emission factors.

Fertiliser application was one of the largest emission sources. Emissions were lowest in calculators A and B (and assumed in D, but uncertain due to lack of disaggregation) and at similar levels implying similar assumptions. In calculators E and F the soil emissions were nearly twice as high as in the other calculators implying they use different methodologies to calculators A and B for calculating nitrous oxide emissions factors from soils.

Crop residues was one of the smaller sources of emissions. These emissions were variable between the calculators. The highest value was seen in calculator A, which was five times higher than the lowest value in B. Calculator D was twice as high as calculator B, and calculator E had an intermediate value between A and B. These differences in emissions between the calculators imply different assumptions and approaches being taken by each calculator.

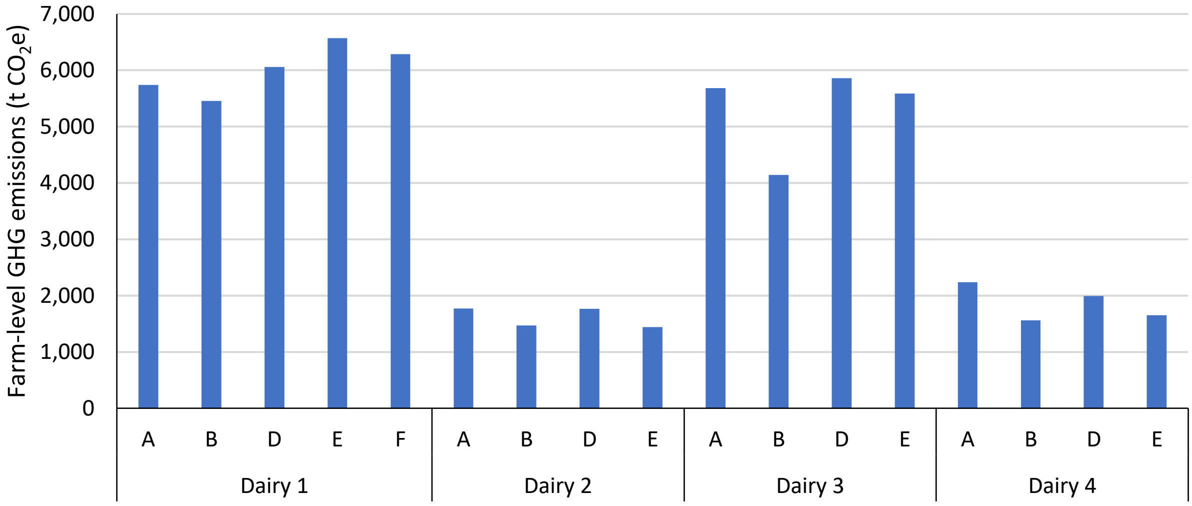
Fuel emissions ranged from approximately 250 t CO_2e in calculators A and E to 327 and 385 t CO_2e in calculators D and F.

Pesticide production emissions differ between the calculators, with higher results observed in B and F; however, these emissions were generally 1-2% of overall emissions so had negligible impact on overall emissions.

Carbon stock change was variable, with carbon stock gains in D and E (a very small gain) and carbon stock losses in A and F. How the calculators accounted for soil management practices (e.g. cultivations and residue return) and whether they accounted for woodland affected the stock changes reported. Calculator B did not offer the opportunity to capture changes in carbon stocks for the practices that were present on this farm.

Dairy model farms

The farm-level emissions for the **dairy** model farms are presented in *Figure 3*. Calculator B tended to have the lowest emissions for all model farms, while calculators A and D tended to have similar values. Calculator F was only assessed for Dairy 1 but gave the second highest emissions. With the exception of



calculator B for Dairy 3 there is, at a high level, relatively little variation between the calculators on dairy farms. These similarities in total emissions do hide important differences in methodologies used, these differences which may, in turn, affect the sensitivity of the calculators to management practices and the inferences farmers will derive regarding potential efficiencies and the relative impact of mitigation options.

Figure 3. Farm-level emissions for dairy model farms (without carbon stock change)

The farm-level net emissions for ***Dairy 1***, including carbon stock change, are disaggregated into the major emission sources (Figure 4). Note that calculator D combines *Enteric* and *Manure* emissions in their output (under the name of the specific livestock class they are associated with); in the outputs in the figure below these are presented under *Enteric*. The differences in the farm-level emissions were mainly driven by the *Enteric*, *Manure* and *Feed* emissions.

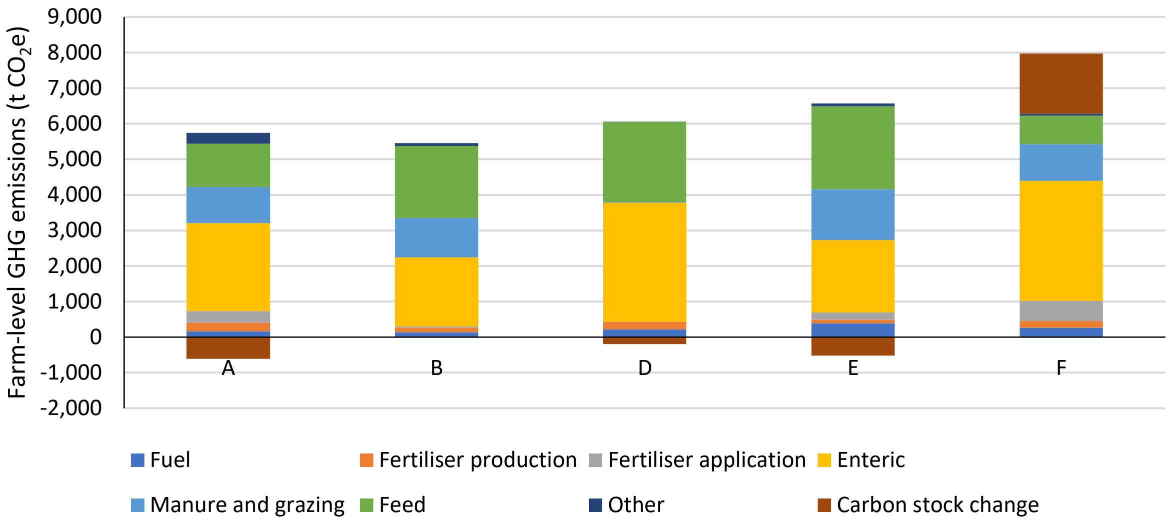


Figure 4. Emission breakdown for Dairy 1 (including carbon stock change)

Enteric emissions were the largest emission source for most calculators. Calculators B and E had similar enteric emissions, with calculator F having enteric emissions approximately 70% higher than these, and calculator A having intermediate enteric emissions. Calculator D had combined enteric and manure emissions, when compared to the combined results in calculators A, B and E the totals were similar. All calculators are using the methodology set out in the either the 2006 or 2019 version of the IPCC guidelines, but it appears that this is being implemented in different ways, due to differences in how feed data is collected and how livestock inventories are compiled.

Feed emissions were more variable with a threefold difference in feed emissions between the calculator with least (805 t CO_2e in F) and those of B, D, and E which had the highest emissions (2,017 t CO_2e, 2,251 t CO_2e and 2,326 t CO_2e, respectively).

Manure and grazing capture the emissions from manure management in housing and the emissions from manure deposition in the field (as few calculators disaggregated these). Calculators A, B and F had similar manure emissions (1,014 t CO_2e, 1,106 t CO_2e and 1,034 t CO_2e, respectively) suggesting that they were following a similar methodology while calculator E had slightly higher emissions (1,438 t CO_2e). Calculator D aggregates manure emissions and enteric emissions in its output – see comment in 'Enteric'.

The calculators vary in how they account for ***Carbon stock change***. Calculators A, D and E calculated sequestration (through woodland) whereas calculator F focused on losses of carbon stocks due to soil carbon emissions from arable and grassland. There was variability in the other emission categories, but as their overall contribution to the farm-level emissions is small, these are not explored in detail.

It is important to note that calculator F is an outlier for both enteric and feed emissions, but the high enteric emissions counteract the low feed emissions resulting in similar overall emissions to the other calculators – this calculator uses older methodologies and emission factors than the others. The similarity in overall emissions (when excluding carbon stock change) is not necessarily as a result of true harmonisation – although it is important to recognise that the dairy sector is the only sector to have sector-specific guidance on emissions assessment via the International Dairy Federation global Carbon Footprint Standard.

Pigs and poultry

The farm-level emissions for **poultry and pig** model farms are provided in Figure 5**Error! Reference source not found.**. The farm-level emissions were highly variable between the calculators.

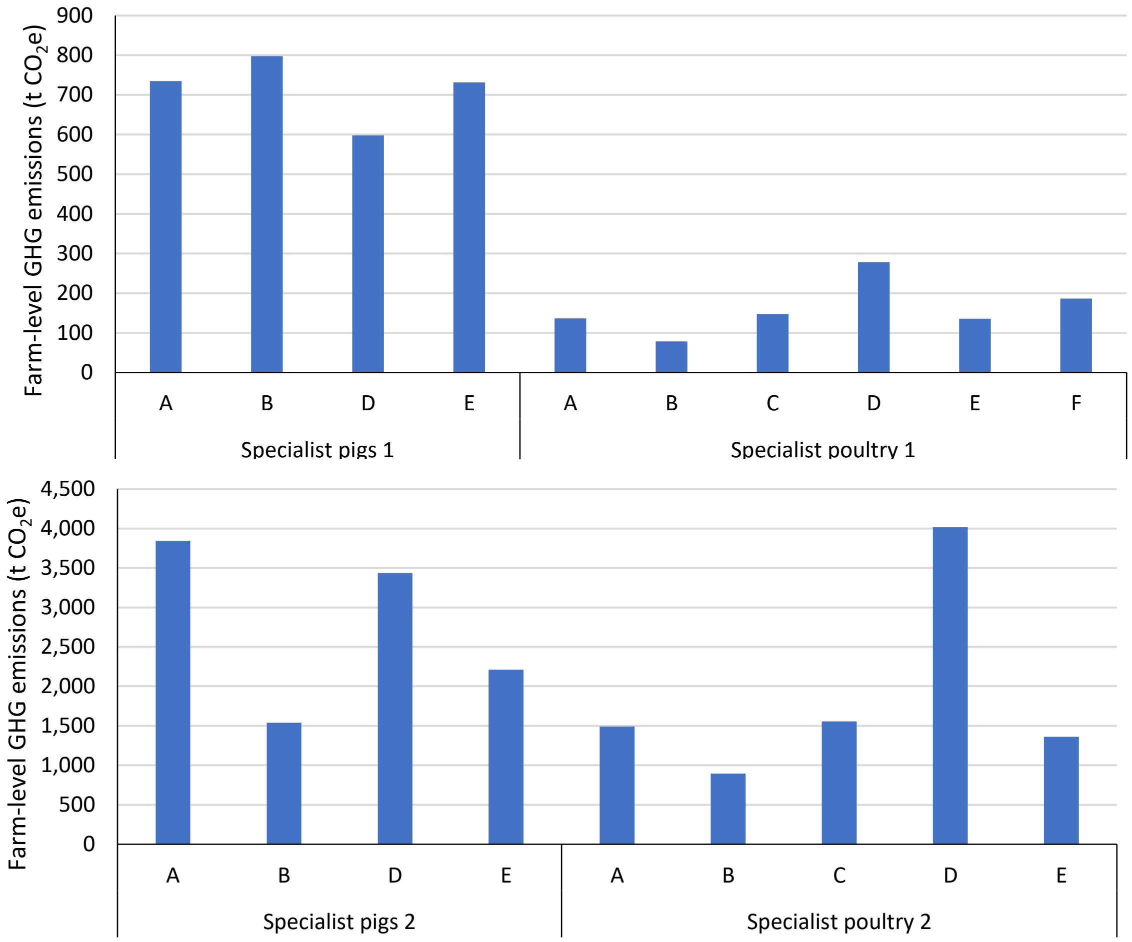


Figure 5. Pig and poultry farm-level emissions (without carbon stock change)

The emissions for ***Specialist Pigs 1*** (indoor) and ***2*** (outdoor) show contrasting patterns; ***Pigs 2*** has much more variation in results than ***Pigs 1***. Calculator B has the highest emissions for ***Pigs 1*** while it has the lowest emissions for ***Pigs 2***; this is driven mainly by calculator B assuming high manure emissions in the indoor system but only having limited capacity to account for field emissions from the manures in the outdoor system. Calculator A has high emissions for both pig farms, and while emissions for calculator E are equal to calculator A for ***Pigs 1***, they are a little over half for ***Pigs 2***. For ***Specialist Poultry 1*** and ***2***, a similar pattern was seen across the calculators; calculator D had emissions over twice as high as the other calculators for both farms, while calculator B always had the lowest emissions, and calculators A, C and F all had similar emissions at the aggregate level but important differences when disaggregated to emissions sources.

The breakdown of emissions for ***Specialist Poultry 1*** (Figure 6) demonstrates the factors driving differences in the outputs of the calculators. Although there is variation in *Manure*, *Fuel & Electricity*, and *Other*, the *Feed* category is the largest source of difference between the calculators. While several calculators (A, C, E, and F) have quite consistent feed emissions (between 89 and 118 t CO_2e) the feed emissions for calculator D (231 t CO_2e) are nine times higher than in the lowest, calculator B (27 t CO_2e). The *Other* category captures a range of small emission sources including bedding, enteric emissions (only in calculator F), embedded emissions in the purchased chicks and 'medicine' (only in calculator C). ***Poultry 1*** was a full-housed system therefore no carbon stock changes were included (though note that carbon stock changes were included in the embedded emissions in some of the inputs, such as the land use change emissions in feed).

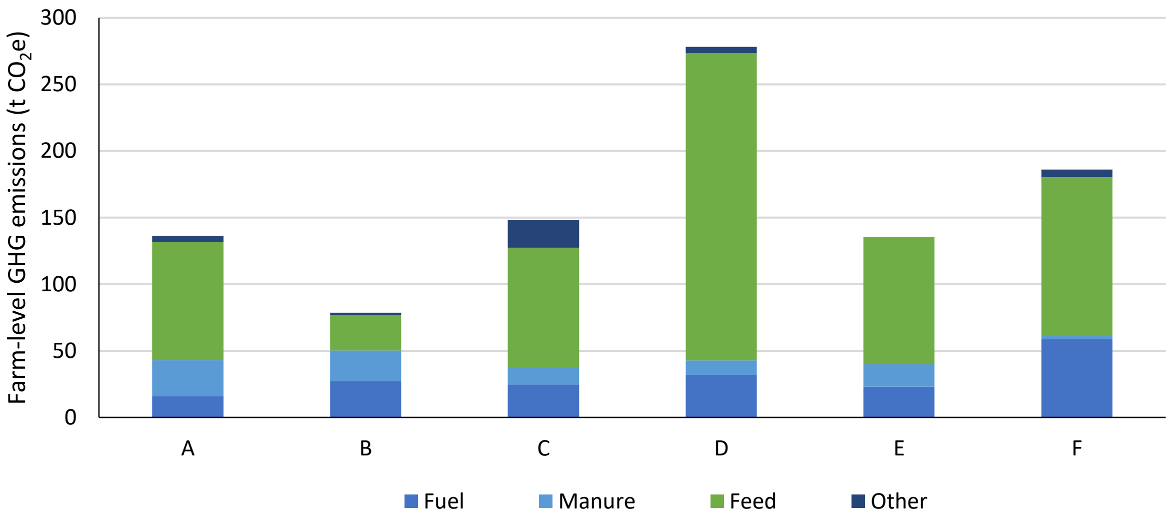


Figure 6. Emission breakdown of Poultry 1. Housed system without carbon stock change.

Mixed farms, lowland and LFA grazing

The farm-level emissions for the remaining model farms (***Mixed 1*** and ***2***, ***LFA 1*** and ***2***, ***Lowland 1*** and ***2***) are presented in Figure 7. Aside from ***LFA grazing 2*** where emissions were similar across the calculators, there was either no alignment among the calculators (both mixed farms) or there was a single outlier (calculator A in ***LFA grazing 1***, calculator B in ***lowland grazing 1*** and calculator D in ***lowland grazing 2***). The differences among the calculators could, to some extent, be explained by the factors already discussed in this results section. However, within the constraints of this project, it was not possible to identify the causes of the high level of divergence of the outliers.

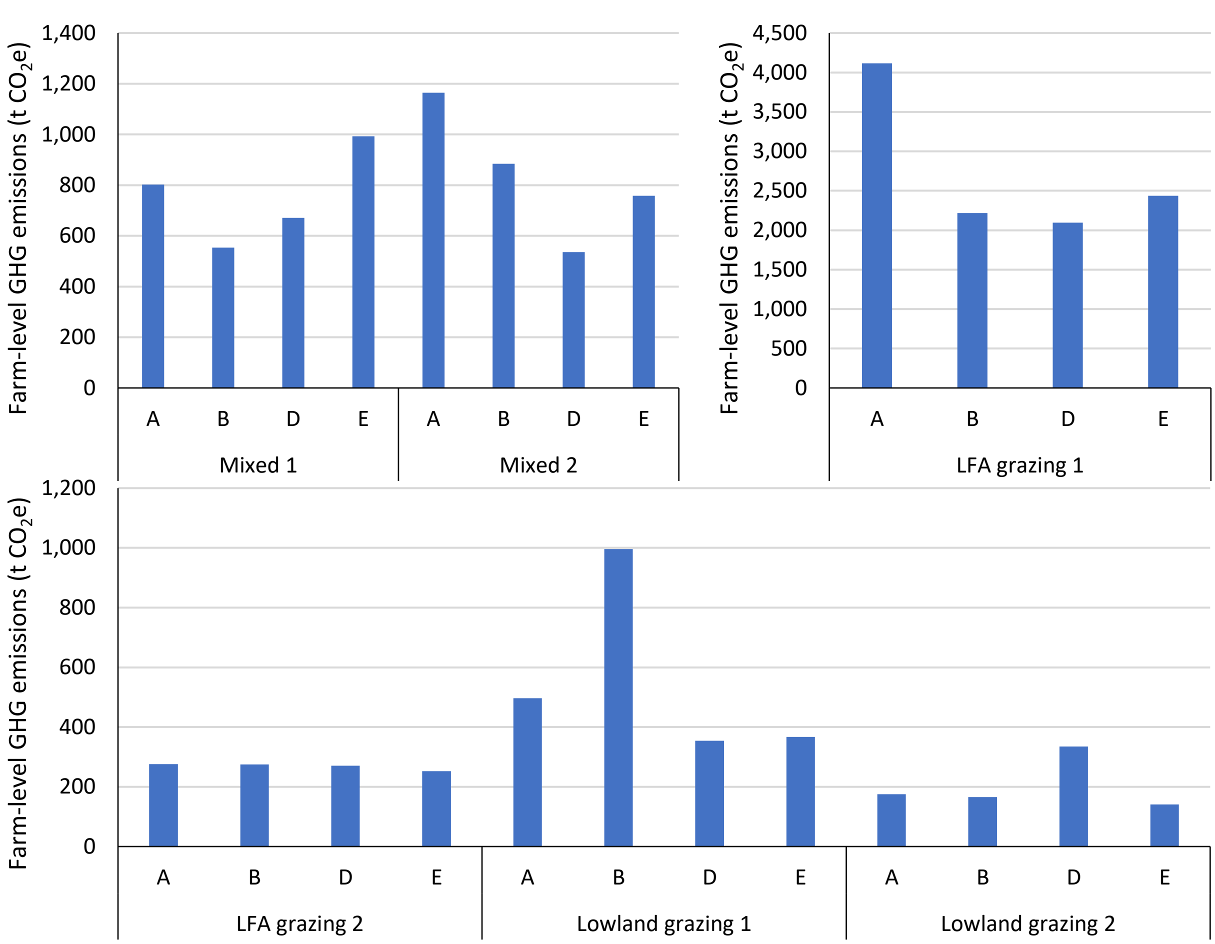


Figure 7. Emission breakdown for the LFA farms, the lowland grazing farms and the mixed farms (without carbon stock change)

Main sources of divergence

The key sources of divergence between the tools are presented in Table 6. Broad recommendations are provided for how these sources of divergence can be tackled in order to bring about harmonisation. This is explored in more detail in the next section.

Table 6. Key sources of divergence between the extreme values of outputs in some calculators.

Category	Details	Affected systems	Recommendation
Carbon stock change	Large variation in how calculators account for carbon stock change and what aspects of removals or emissions are modelled: • Land use changes • Emissions / removals from above ground biomass (woodland, hedgerows) Emissions / removals from below ground – soil management practices	Soil based systems and systems with perennial vegetation, e.g. woodland.	Calculators should include carbon stock changes using higher Tier (II or III) methods – aligning with latest guidance on this (e.g. SBTi and GHG Protocol LSR guidance). • Ensure emissions from land management – e.g. cultivation of peat soils is included as a minimum. • Define clearly which non-crop/grazing land should be

			included in farm-level carbon assessments – e.g. woodland, agri-environmental schemes. • Where removals are captured ensure that robust, peer reviewed methodologies are used (e.g. Woodland carbon code). Calculators to clearly display information on uncertainties linked to removals so user is well aware of how the data presented can be used.
Crop residues	Calculators are variable in their assumptions of the quantity produced and quantity remaining on the field after baling.	Arable systems.	Provide UK standard figures for calculating typical crop residues with and without baling. Give clear guidance on what residues should be included in assessment.
Enteric	These emissions are driven by livestock numbers, amount and type of feed, and assumptions made by the calculators.	Ruminant livestock systems.	Collect feed data by group of cattle (e.g. age group) to ensure methane calculations are specific to each group. Directly link feed data to enteric methane calculations. Ensure enteric methane emissions are presented separately.
Feed	The embedded emissions in feed are variable. This is particularly true for soya-based feed and whether land use change (LUC) emissions are included.	Livestock systems using purchased feed, particularly those using soya-based feed.	Provide guidance on use of standardised database e.g. GFLI. Ensure LUC emissions from purchased feed are included.
Fertiliser application	Soil-based nitrous oxide emissions from the use of nitrogen fertilisers vary between calculators due to IPCC emission factors used and sensitivity of the methods to fertiliser types and climate conditions.	Arable, horticulture and grazing systems.	Use nitrogen fertiliser data in sufficient detail to be able to model soil emissions from different sources of nitrogen. Employ Tier III models or Tier II models aligned with the nitrous oxide emissions UK GHG Inventory method.
Fertiliser production	The embedded emissions in purchased nitrogen vary. Two	Farms using manufactured nitrogen,	Use latest emission factors provided by

	calculators were using out-of-date emission factors.	particularly arable production systems.	Fertilizers Europe or fertiliser suppliers. Ensure regular update process in place to maintain emission factors
Manure	Calculators differed in how they account for manure quantity and management practices; some had greater user ability to define what happens to the manures.	Livestock systems and arable systems using organic manures.	Increase data entry granularity. Include appropriate manure storage, application and export functionality.
Other emissions	For other emissions in the system, where the proportion of emissions compared to those from nitrogen fertilisers and enteric methane is relatively low, on most farms there are differing approaches taken to the inclusion or exclusion of these elements – which include capital items, consumables, transport of raw materials and waste management. The older PAS 2050 standard does not consider capital goods to be within scope, whilst the newer ISO 14067 says that they should be included based on significance (materiality). The GHG Protocol Land Sector Guidance says that capital goods should be included in assessments. Whereas all the above require emissions from waste management to be included in assessments.	Potentially all systems, though some will be more affected than others depending on the extent of capital items, consumables, etc. used.	Provide clear guidance to calculators on where capital goods and consumables should be included in assessments. This will also require guidance on what should be included and potentially the creation of a standard database of emission factors for widely used capital items. Include requirement in minimum basic standards for calculators to include management of waste and transport of raw materials.

Analysis

As can be seen in the figures presented in the results section, there is variation between the carbon assessment calculators in both the overall emissions calculated for the model farms and also in the breakdown in the contribution of the different emission sources. In this section, the reasons for these differences are explored. Given the complexity of the calculators, it is not possible to consider all the factors leading to differences in outputs. Instead, several themes were identified that explain why there are differences between the calculators: 1) System boundaries; 2) Data entry factors; 3) Emission factors; 4) Calculations and assumptions; 5) Land-based carbon removals and emissions; and 6) Support for mitigation.

System boundaries

The system boundary refers to the processes and activities that are captured in the carbon assessment. Broadly speaking, there are three components to this: upstream emissions and removals (those embedded within purchased materials), emissions and removals occurring on the farm, and downstream emissions and removals (those that occur post farm gate). In order to be able to use a calculator well, a user needs to understand what it is they are assessing (whole farm, enterprise or product) and why (e.g. to inform their decision making or to meet corporate reporting requirements, such as the SBTi Scope 3 reporting).

This report considers farm-level carbon assessments. Given that farm businesses can cover non-agricultural activity alongside farming, defining what should and should not be covered by the assessment is important. For the purpose of this project, the assessments focused on only the agricultural activities that take place on farm and the linked non-commercial woodland on the farmed area while other diversification activities were excluded.

Although the calculators are focused on the actions specific to farming, there are differences in what farming enterprises they are able to include and whether sufficient detail is provided to accurately model that system (e.g. calculator A offers soft fruit assessments, but not for soilless systems whereas calculator E covers soft fruit assessments for both perennial systems and soilless controlled environments). The activities covered form an inherent limit to system boundary definition within a calculator. Users therefore need to be able to select a calculator that covers the enterprises on their farm. The calculators also differed in how they considered activities linked to agriculture (e.g. calculator B captured fugitive emissions from manures in an anaerobic digestor, but the management of an anaerobic digester was only covered by calculator E). Non-farming activities were included in some calculators; an example of this is whether the calculator enables inclusion of woodland management within the carbon footprint.

Specific farm-level guidance is needed to define boundaries around how farms consider aspects such as short-term rented land (e.g. for potato production), rotational emissions (e.g. lime applications), diversification activities (e.g. energy use for camping sites), production of renewables (sold to grid), temporary grazing (e.g. of cover crops by another farmer's stock), contractor fuel use, on-farm processing (e.g. anaerobic digestion of manures or crop residues, packhouses), and the area of forestry or woodland included. Clearly defining what is meant by a farm-level assessment and what aspects of the farm business should be included or excluded will enhance harmonisation of data entry. Once it is clear what a farm-level assessment should include as a minimum, it is important that the calculators have the functionality to be able to align with that basic standard. Defining what should be included in a farm-level assessment will depend on how industry and HMG wish to use this data.

The specific standards that the calculators are aligned to define the system boundaries. The standards are designed for individual bespoke assessments, whereas the calculators by their nature have a certain level of automation. The standards require the need to capture all relevant emissions (for example, the PAS 2050 guidance allows exclusion of emission sources below 1% of the total system emissions whereas the more recent ISO 14067 says that exclusions are permitted if they do not significantly change the conclusion of the assessment), but they are unable to define exactly what should be included and excluded. The calculators are designed to support the user in determining what to include and exclude according to the standards that they follow. Decisions about system boundaries can be included as part of the 'user journey' where users can be helped to determine what to include by the calculator itself (e.g. in the user guide), by the calculator providers, consultants or in discussions with supply chain as to their data requirements. This was not considered in the assessment. The calculators are mostly aligned in what they include within the system boundaries (e.g. all include emissions related to enteric fermentation, manures, fuels and fertilisers); however, there are some differences in what is included and how the calculator is set up to facilitate the user to include the relevant emissions.

Initially, many of the older calculators were designed to align with PAS 2050:2011. However, this standard has not been updated since 2011, having been superseded by ISO 14067. The shift in thinking from emissions assessment to Net Zero has led to changing needs from the calculators as the public and private sectors start to want to understand carbon removals as well as emissions. This has led to the development of the SBTi guidance, and the development of the GHG protocol Land Sector and Removals guidance (still in draft form at the time of assessment) in recent years. There is increasing pressure for calculators to align with these more modern standards. Currently, only calculator E is aligned with the needs of these as well as PAS 2050. Another reason to move beyond the PAS 2050 standard is that it was designed for product-level assessments, not organisational-level assessments (e.g. a farm-level assessment), and therefore an organisational-level assessment standard is more appropriate for these calculators. However, where the calculator also offers product-level assessments, the calculator should align with an up-to-date product-level assessment standards (e.g. ISO 14067 or the GHG Protocol Product Standard).

In earlier agricultural carbon assessments, capital items, consumables, transport and waste tend to be excluded as they are 'assumed' to be insignificant in proportion to the other emissions. However, in certain systems these may contribute sufficient emissions for it to be necessary to include them. For example, horticultural systems with extensive infrastructure, such as glasshouses, and consumables, such as fleece, module trays, growing media may need to capture these within the assessment. There were only three calculators out of six assessed that captured emissions from capital or consumable items, while three of the six captured some elements of waste management, and two of the six captured transport of inputs.

Capital items and materials were excluded from the model farm assessments so that the elements that were present in all calculators could be compared, and so the range of emissions across the tools is not artificially inflated. But, for example, the poultry assessments in calculator C included emissions for 'medicine' and embedded emissions in chicks, which represented approximately 5% and 4% of total emissions respectively, suggesting that they are relevant and should therefore be included in poultry assessments. Furthermore, in systems where there is a high level of control over conditions (e.g. housed broilers or glasshouse systems), options for reducing emissions may be more limited and require targeting minor emission sources; capturing these therefore becomes more important.

The system boundaries did vary with regards to carbon stock changes. Although all calculators offered the option to capture carbon stock change in trees, some limited this to trees within the field boundaries, while others allowed areas of woodland to be included within the system boundary. The calculators were also very different in which carbon stock changes were considered in the system boundary (e.g. whether emissions from farming on drained peat were within the system boundaries). These are considered in more detail in the *Land-based carbon removals and emissions* section.

Linked to this are the emissions associated with non-farming land use enterprises, such as those for biodiversity restoration (e.g. growing flower-rich margins or providing winter bird food). This includes fuel use for establishment and nitrous oxide emissions from the breakdown of plant residues. In general, the calculators were able to capture emissions from fuel use, though in some calculators this required including the fuel with a different enterprise. Not all of the calculators were able to capture the additional nitrous oxide emissions.

The other aspect of the system boundary to consider is the temporal aspect. Most farm- and enterprise-level assessments are calculated over a one-year period. However, farming activities and enterprises do not always fit neatly into a single year (especially if you are looking at product- rather than farm-level assessment). There is a cyclical nature of production that means that actions that occurred in one year might have impacts in future years. For example, rotational aspects of fertility where lime or manures are applied in one year and the benefits are felt over a number of years. This means that if you only look at the application of lime or manures in the year of application, the user may allocate all the application to the crop in that year and nothing to the following year's crop, when in actual fact the following year's crop will also benefit. Perennial crop production requires a planting and establishment phase before the productive phase begins, and then there is a removal phase too. If there is regular establishment, production, and removal on rotation across a whole farm, then these might be captured in an annual assessment. But if this is not the case, or a product assessment is being completed, then there is a requirement to capture these in separate assessments and combine them pro rata in order to capture the whole process. Manures tend to be produced one year and then stored and applied in the following year, and, in a similar vein, feeds tend to be grown in one season and fed over the following year. There is the potential for better tracking of flows across the farm system that take place across years (e.g. an arable system producing feed for livestock in the following year, the livestock producing manure that is used on the following year's crops). However, this is difficult to capture in the calculators due to the data requirements and the risk that a data issue at one point in the system will flow through causing issues elsewhere. These flows mostly tend to be captured by assuming a one-year snapshot of the farm would be representative of past, present and future years. A more detailed approach to capturing these rotational emissions was seen in calculator E which included all rotations (in arable systems), for establishment and removal phases (e.g. in perennial systems), and attribution of the emissions mentioned above across the appropriate crops (in the rotation) and productive phases (in a perennial system).

Temporal boundaries were generally consistent between tools, as farm-level assessments are completed on an annual basis, but there were some differences in modelling livestock systems for part of a year that created challenges. In product-level accounting, the temporal boundary becomes more important. Where farm-level assessments are used to create product-level estimates, the calculators limited to annual timescales present challenges for some livestock systems. Systems such as poultry meat production have very short cycles from placement of chicks through to slaughter and clean down of less than two months, meaning that multiple cycles can take place in a year. However, because the cycles are not constrained to an annual cycle they do not neatly fit into complete number of cycles per year, meaning that an annual assessment may include a partial cycle. Poultry egg production tends to have a 72-week cycle meaning that an annual assessment does not truly reflect the whole of the process. It is possible in calculators B, C and E to calculate emissions for an individual livestock lifecycle that is less than a year in length; calculator C can present this data both in terms of annual (pro-rata) and total cycle basis.

In beef production it can take two to three years for an animal to reach slaughter weight. In a suckler beef system where the cattle are born and raised on-farm and the system is fairly static, it is possible to capture these emissions by assuming a snapshot of one year represents the whole life cycle. However, where either the suckler system is changing, or in a finishing system with animals being purchased in and grown for a period of time and then sold again, the purchased animals should arrive with an embedded footprint from their dam (i.e. their mother) and their first months (or years) of life. However, due to the complexity of calculating embedded emissions from livestock, at present none of the calculators assessed included embedded emissions from purchased stock (with the exception of calculator C, which included chick and pullet embedded emissions). This therefore means that, other than for the poultry systems, it is not a cause of difference in the results, but it is a significant omission for some systems. The lack of embedded emissions from purchased stock can potentially result in a large underestimation of the total emissions from farm, enterprise, or product and has significant implications for the ability of supply chains to accurately use data produced in their corporate reporting. One of the calculators attempted to avoid this issue by providing emissions per kg liveweight *gained* that year rather than kg liveweight; this way, they recognise the absence of embedded emissions. However, this approach does not comply with the standards for product- or farm-level assessments.

When embedded livestock emissions are included within an assessment, care must be taken to avoid double counting in situations such as where livestock is being moved between multiple farm units that are part of the same farm business. This risk is also present where livestock is temporarily moved between farms, such as when grazing sheep on another farm's cover crops. The GHG Protocol Agricultural guidance suggests that emissions are counted as Scope 1 for the farmer whose land is being grazed and Scope 3 for the owner of the livestock (GHG Protocol, 2017). This creates the risk of double counting and therefore needs to be considered when aggregated emissions from multiple farms. Awareness of this risk of double counting is also important for other materials moving between farm units. This includes feed and bedding grown in one farm unit and used for livestock in another farm unit, and any manures moving in the opposite direction.

Conclusion: Clear guidance is needed as to what constitutes a farm-level carbon assessment, how the user should deal with agricultural and non-agricultural enterprises on farm, inclusion of non-cropped areas such as woodland and forestry, and complexities around rented land to ensure that the data that is used in the calculators is consistent. It is also important there are clear minimum standards of what should be assessed within a farm-level carbon assessment and the requirements for inclusion of embedded livestock emissions, capital items and consumables. When supporting users in the completion of assessments having explicit guidance available as to what should be included as a minimum in terms of non-agricultural activities will aid consistency of assessments. However, it also remains important that farm businesses are able to retain the ability to assess wider aspects of their overall estate for other purposes, e.g. corporate reporting of their total business emissions.

Recommendations:

- Industry and HMG to define what a farm-level assessment is, what it should include and exclude and how the emission outputs are to be used.
- Calculators should align with the system boundaries set out in the latest standards and the system boundaries need to be clearly stated.
- Consider options to work with industry to provide guidance or signposting to users as to what should and should not be included in the assessment boundary for different agricultural systems and purposes – e.g. farm vs product, alignment with SBTi/FLAG, GHG Protocol.
- Consider options to develop robust approaches to calculating embedded emissions from purchased stock, or support development of mechanisms to transfer assessment emissions from one farm (e.g. breeder) to next (grower) and next (finisher) to support more complete and transparent livestock carbon emission assessments.
- Ensure users are aware of the implications for corporate reporting if embedded livestock emissions are not included in assessments - this is particularly important in finishing systems, where stock of various ages are purchased and then may only spend short periods of time on the finishing farm prior to slaughter.

Data entry factors

Data collection and entry for the assessment of a full and detailed farm-, enterprise- or product-level carbon assessment is a difficult task due to the complex nature of many farming operations across both temporal and spatial aspects of farming. However, the calculators are typically aimed at non-expert computer users (the farmer, for example) and therefore have to simplify data entry to a certain extent to enable the user to interact with the calculator and generate a useful result. The development of the calculators has often been led by the data the users already have or are able to collect easily. Often, the simpler the data entry is, the more user friendly it is, but also the more assumptions the calculator makes about the farm. This makes it less representative of the farm, and therefore less accurate and precise. Recent software developments within calculators can reduce the need for complexity and at the same time can deliver good user experience and accuracy.

There are a number of examples of where simplification occurs within the calculators. For example, in the ***livestock data***. Ideally, to create an accurate assessment (over one year for a farm), you would need to know exactly how long each animal was present on-farm across the year. Ideally, the calculations need to know the birth date, weight of each animal at different stages of its life, how long it stays on-farm, and weight at sale or slaughter for all animals on-farm in order to calculate accurately the total manure produced and the associated enteric emissions. However, especially where there is all-year-round calving or farrowing, regular chick placements or purchase and sale of stock, this is not practical data to record and input, and would create a barrier for many users from accessing the calculators. Instead, the majority of calculators simplify this request to the average number of animals on-farm for the year, and then either an average weight, or a weight at purchase and slaughter or sale. For example, a farm may have a group of 100 pigs for eight weeks, which would be entered as an average of 15.4 pigs for the year with 100 bought and 100 sold. However, this approach relies on the user to do calculations outside of the calculator, which has the potential to lead to errors, especially in complex systems where there are multiple batches of animals coming onto and leaving the farm in any year. Third party validation of this data can be very difficult if there is no record of how the calculations have been made. In contrast, calculator E provides a flexible system for data input that permits the user to provide the data at whatever level of granularity they have recorded.

If a user is using the assessment for themselves and takes a consistent approach to calculating livestock numbers each year using the same calculator, the impact of calculation method is minimal. However, if the user is sharing their results with a supply chain where other suppliers are calculating livestock numbers in different ways, or the user switches to a different calculator with a different way of entering the livestock (e.g. different classes or categories of animals defined), then it becomes more difficult to make comparisons. The granularity of livestock data entry will also impact these calculations. At present most of the calculators restrict users to entering a single group of each class or category of animals, and then assume that you treat all the animals in that group the same with regards to, feeding, housing, growth rates, etc. However, on real farms groups of livestock may be managed differently if bought in winter versus summer, or in accordance to how they are performing. By grouping all the animals of a particular class or category together there is a loss of granularity in the data entry which may impact on calculations and results. The ability for users to define specific categories (e.g. for different cohorts), such as is available in calculator C (where poultry barns/houses are considered separately) and E (where the user can define cohorts for all types of livestock), provides more opportunity to better model emissions. Some livestock enterprises show a high level of genetic variability (e.g. the wide variety of sheep breeds), which could influence emissions through different energy and feed requirements, and growth rates. The calculators were limited in their consideration of livestock breeds (e.g. calculator B did capture breed for dairy systems but not for other livestock); however, being able to split up livestock into categories and set specific parameters for these does enable those differences in breeds to be accounted for without the need for the user to specify the breed.

Livestock feed is another area where data entry processes differ between calculators. Calculators A and D ask for total volumes of feed purchased for an enterprise, whilst calculator B asks for the daily dry matter intake (DMI) across grass, conserved forage and concentrates per class or category of animals. Calculator E asks for time at pasture and the percentage contribution of each ration ingredients to total feed rations, with the calculator determining feed intake quantities based on the weight gain of the livestock (alternatively, it does allow fresh weight quantity consumed daily for each ingredient). These different approaches have different implications. Knowing the total purchased volume of feed helps you to understand if there are opportunities to reduce waste, as if the volume purchased or used far exceeds the volume required by the stock there is an opportunity to increase feed efficiency and reduce waste. However, this approach does not allow a direct allocation of those feeds and volumes to specific groups of livestock and instead the calculator has to make assumptions. If actual DMI values are given per class of animal then it is possible within the calculations to directly link feed to class of animal, and therefore trace digestibility and nitrogen content. However, these values are based on the volume consumed not purchased, so do not allow transparency over volumes of wastage.

The granularity of livestock data entry and associated feeding data has implications for both enteric fermentation (ruminants) and manure storage and application emissions. The nutrient content and digestibility of feed impact both these calculations; therefore, the more accurately you can link the diet data to the livestock class, the more accurate the assessment can be, and the more responsive it will be to changes in practice. Calculators B and E link diet data to enteric emissions, but whereas calculators E has a nitrogen balance that links the nitrogen content of diet through to manure emissions, calculator B does not. Although calculator A does not link enteric methane directly to diet composition, it does ask for information on the digestibility and crude protein content of the diet at livestock class level, which can be used in the enteric and manure emission calculations.

The way that data on ***manufactured fertilisers and organic manure applications*** is entered into the different calculators varies. At its most simple, the calculators ask for total volume of either urea-based or ammonium-based manufactured fertilisers used on a crop (calculator A), and the proportion of nitrogen in those applications. In the more detailed data entry of some calculators, it is possible to select specific products (even down to manufacturer in calculator D) and either enter rate of application by nutrient or by product (calculator B). Calculators B, C and E have an API connection to farm management software allowing the import of data, reducing manual data entry, and this is an option being developed in calculators A and D. Some calculators allow the user to choose an input method (e.g. units) whereas others only allow a single method – depending on the existing farm data management approach, this may require calculations to be made by the user.

Organic manures are captured in different ways within the calculators. In the majority of the farm-based calculators it is assumed that all the organic manures that are produced on-farm are applied on-farm (unless specifically marked for export), ensuring that all the emissions from manure application are captured. However, in the product-level assessments, where there is potential for manures to be used elsewhere in the rotation (i.e. not just on grassland that the stock are grazing) there is the need for the user to accurately calculate how much manure is applied where, otherwise there is a risk that emissions will either be over- or under-estimated if allocations are made incorrectly. The biggest risk being that emissions from manure application are missed due to failure to capture applications on all forage crops. When applying the organic manures in the calculators, different approaches are taken. Calculators A and E ask the user how much nutrient (nitrogen in particular) is present within the manure while providing user-visible default data for all manure types, and others (such as calculators B and D) use a default value for nitrogen in the manure, meaning that the user needs to ideally adjust application volumes if they know the assumed nutrient value is wrong (though in some cases the calculator does not make it clear what the actual N content assumption is, e.g. calculator D). This means the user needs to understand the importance to the assessment of nutrient content versus volume of manure.

Conclusion: Where data entry is complex, leaving users to make calculations outside of the calculator, such as for livestock numbers, it leaves opportunity for inconsistency in approach to data entry assumptions or errors in data entry. There is a fine balance to be struck between simplifying data entry to make calculators accessible to users and losing functionality and the ability to properly link aspects such as feed content and quantity to livestock data. The calculators may be using the same basic IPCC 2019 guidelines to make the calculations, but the assumptions that link the data entry to the calculation are different. Supporting and incentivising users to collect more specific data (e.g. on livestock weights and feed) would allow better quality calculator outputs. It could also provide data for driving better decision making and productivity, creating a 'win-win' situation of reduced emissions and improved financial performance.

Recommendations:

- Consider options to facilitate the sharing of farm-level information between different software systems and calculators to minimise the cost of acquiring data and the burden on farmers of entering similar data in multiple places.
- Calculators may consider developing functionality to guide users through those calculations within the calculator itself or enable linking to actual farm records to enable the calculator to accurately create the required numbers.
- Consider the clarity and transparency of documentation on assumptions that calculators are making, as well as the methodology they are using.

Emission factors

Emission factors are defined by IPCC (IPCC Glossary, 2019) as '*a coefficient that quantifies the emissions or removals of a gas per unit activity. Emission factors are often based on a sample of measurement data, averaged to develop a representative rate of emission for a given activity level under a given set of operating conditions*'. Generally, the calculations in the calculators work by the user providing the activity data and the calculator providing the emission factor (though some calculators allow user-inputted emission factors). There are two types of emission factors that are used in the calculator: those associated with the embedded emissions from purchased products and those for calculating on-farm emissions. The on-farm emission factors range from simple (e.g. combustion of fossil fuels) through to the complex calculations for methane and nitrous oxide (e.g. IPCC emission factors for the proportion of nitrogen fertiliser lost as nitrous oxide via direct emissions). In this section we just consider the embedded emissions and those associated with energy use on-farm.

For embedded emissions, there is rarely a single definitive emissions factor for any particular item. Key embedded emission factors that are required in the assessment of emissions from agriculture include purchased products, such as manufactured fertilisers, plant protection products, feeds and even purchased livestock. The creation of emission factors for embedded emissions are effectively carbon assessments in their own right; this means that there is inherent uncertainty in the accuracy of any emission factor that is used. The relevance of an emission factor to a particular farm is determined by both spatial (i.e. is the emission factor representative of that location and system) and temporal (i.e. is the emission factor representative of the system at the time of assessment) granularity. For raw materials that are purchased by the farm, the ideal approach is to have the actual emission factor for that raw material provided by the producer of the raw material; however, in most cases for simplicity calculators tend to have a simplified list of materials (e.g. types of manufactured nitrogen fertilisers) and associated emission factors.

For energy use (i.e. Scope 1 emissions from combustion of fuels on-farm, Scope 2 emissions from electricity and the associated Scope 3 emissions for both), the UK Government publishes data tables of emission factors (referred to as Conversion Factors). These tables are updated annually to reflect changes in production practices (e.g. changes in the proportion of different energy sources used in grid electricity). These are widely used by the calculators. These data tables also contain emission factors to use for waste, materials and transport.

Given that these emission factors can also change over time (e.g. the energy mix for grid electricity varies on an annual basis resulting in difference in the emission intensities between years) it is important in some instances that the emission factor from the appropriate year is allocated to the assessment (e.g. calculators C, D and E determines which energy emission factor to use depending on the assessment year).

A key driver of differences in the calculators' emissions in arable production systems was the ***fertiliser manufacturing emissions***. There is no definitive list of emission factors for manufacture of fertilisers and therefore it was found on analysis that there were different emission factors being used. The most significant impact was the age of the emissions factor. Over the past 10-15 years, the adoption of abatement technology and use of natural gas for fertiliser production in Europe has lowered production emissions. Calculators A and F were using emission factors that pre-dated these changes resulting in much higher embedded emissions being included in their assessments (as can be seen in the breakdown of emissions for Cereals 1). Other calculators tended to use the figures from Fertilizers Europe's calculator (e.g. as presented in Brentrup et al., 2018). In calculator D there was an option to select the brand and type of fertiliser used, meaning that the user could potentially also make an informed choice as to which fertilisers to purchase at a more granular level than in those calculators that only allowed selection of type, or in one instance merely separated by urea or other nitrogen source. However, for this approach to be useful, it is important that the emission factor database is kept up to date and the manufacturers of those fertilisers continue to update their emission calculations. It is important to note that the emission factors for the specific blended brand fertilisers are unlikely to differ much from the default European-manufactured emission factors for their ingredients, however, they do give an easier approach to entering blended fertilisers. This is, therefore, a situation where the calculator is offering a level of refinement that gives the user the appearance of providing more detail to gain a better output or ease of data entry, but in fact does not materially change the results, at this stage in time.

Another area where there is even greater potential for emission factors to vary and influence results is in ***livestock feed***. The feeds used in livestock production come from a wide range of sources including home-produced, purchased feed from the local area, and international imports. The production systems and practices for production of those feeds, the inputs used, and the assumptions used in the creation of the 'standard' emission factors, are all potentially so variable that this can result in large differences in results.

In addition, there are a number of imported feeds (such as soya) for which land use change (LUC) is a significant part of the overall emission.

There has been some convergence on feed emission factors with calculators A, B, D and E using the Global Feed LCA Institute database of feed emission factors as their main source for imported feeds. This is a paid for database of global feed ingredients. These calculators have then complemented that with feed data from other sources. Other datasets have been used by other calculators (e.g. GESTIM and CAPRI by calculator F). However, even when using the same data source, there are differences in approach to capturing LUC emissions. The impact of this was demonstrated in the ***Dairy 1*** and ***Poultry 1*** model farms where there was large variation in the embedded feed emissions. Dairy 1 used soya from South America assuming that LUC had occurred whereas ***Poultry 1*** assumed there were no LUC emissions (e.g. produced in North America or certified deforestation free). Defining the source of the soya was only possible in three of the calculators (calculators B, C and E) while the other calculators had only a single option for soya. (Note that calculator B has two datasets for livestock feed; the dataset for beef and dairy allows a choice of source locations for soya while for other livestock there is only a generic value for soya.) Where only a single figure for soya was available, there were differences in whether that included LUC emissions or not. Given that the LUC can be considerably higher than the production emissions for growing soya, this greatly skewed the data for model farms using soya.

Compound feed usage also poses a challenge as different compound mixes can contain very different raw materials from different sources. The user may not have sufficient transparency of the feed components to make informed selections within the simplified options available within a calculator to best represent their compound feed usage. Some of the calculators include actual emission factors provided by the feed manufacturers for key compound feeds (e.g. calculator C has NDAs in place with the majority of feed suppliers in the UK and Ireland to access individual ration emission factors). This approach assumes that the feed company has completed an appropriate assessment, but they at least have the accurate information on content and source of ingredients more accessible to them than a user might. This is particularly useful in pig and poultry diets where there is often little influence that a farmer can have over feed choice and limited insight as to what is in the feed they provide. Until feed companies provide emission factors by default on their products, there will continue to be a need for users and calculators to make assumptions about the embedded emissions within livestock feed.

Where feeds are produced on-farm, the whole-farm assessments are able to capture the emissions from that production process, and even the product-based assessments have the potential to complete crop assessments to feed into the livestock assessment (for cattle in calculator B and poultry in calculator C). This allows a more accurate assessment of the actual impact of feed than is possible where feeds are imported.

Conclusion: A key driver of differences in emissions between the tools was the embedded emissions for inputs, in particular for soya feed and nitrogen fertilisers. The use of standard databases (such as the UK Government Conversion Factors for company reporting of GHG emissions or the Global Feed LCA Initiative database) in many calculators has helped to bring greater alignment in emission factors, but there remain differences in how these are implemented and the frequency of updates. Calculators that allow more user specific emission factors to be used, such as linking to specific fertiliser or feed manufacturer's published and validated emission factors, can increase relevance of the assessment to the specific user.

Recommendations:

- Calculator providers to align with the UK Government Conversion Factors, GLFI database (and capture LUC emissions where these are happening) and latest fertiliser emission factors from Fertilizers Europe.
- Consider options to provide greater transparency on the source, age and type of emission factors used in the calculators and how they have been included. It is also, important to encourage transparency over frequency and method of updating emission factors within calculators.
- Consider guidance to users about the importance of emission factors and the way they are managed in calculators on the resulting emissions assessment to support more informed decision making when selecting calculators.
- Encourage livestock feed producers to provide accurate emission factors for their products (including LUC emissions). Calculator providers to increase functionality of their calculators to bring in bespoke emission factors.

Calculations and assumptions

Given the complexity of farm systems, the calculators are required to include calculations to determine data that the user will not necessarily have. Implicit in these calculations are assumptions. There are three main areas – application of nitrogen to soil, manure management, and enteric fermentation – where these complex processes interact with multiple elements of the primary activity data provided by the user. The granularity of the data provided impacts on the assumptions that the calculators make in applying standard methodologies (mostly IPCC 2019).

The different carbon calculators give different results for ***enteric fermentation*** emissions. These differences are driven by a combination of factors:

- the granularity of the livestock numbers and weight data that is collected,
- the granularity of the livestock diet data, including feed type and digestibility, and,
- the interconnectedness of those data entry points with the enteric methane calculations.

All the calculators identify that they are using either an IPCC Tier II or, combined IPCC Tier II/III methodology. This means that they are incorporating dry matter intake and gross energy consumption for each livestock class, as well as estimating the methane conversion factor (proportion of feed energy that is converted to methane). These are complex variables that are affected by several interacting parameters, such as breed characteristics, specific details around feed composition, climatic effects on feed intake and a wide range of factors that affect the rumen microbiome. Therefore, each calculator has to make assumptions, and it appears that the different calculators are using different assumptions based on the way that they collect data from the user.

For example, in the calculators where the feed data is collected at an enterprise or farm level (e.g. D), the calculators have to assume what proportion of each feed type is given to each class of animal that is present on-farm. This approach makes data entry simple for the user but limits the granularly of the enteric methane calculations that is possible. In contrast, where the calculators enable the user to provide detailed diet data per class of cattle (where a class is defined as a group of cattle with similar performance characteristics – e.g. similar age, all lactating, dry cows) this enables the enteric methane calculations to be more directly linked from feeding practice to cattle class (e.g. B and E). Calculator A collects feed data at a farm level and then asks for information on digestibility, crude protein intake and, for poultry, energy intake at class level to feed into the enteric emission calculations; this includes an option for using default values. Where default data (i.e. secondary data) is used instead of user-supplied data (i.e. primary data), there is a loss of granularity. This secondary data introduces the risk of bias based on the training dataset used to develop these values in the calculator. For example, whether this training dataset is location specific or is default global data.

The differences in approach taken by the different calculators have implications for the level of utility that the calculator can provide when it comes to the development of mitigation strategies. Where the calculators are not able to respond to changes in either composition of the diet or quantities fed, this can limit their ability to demonstrate the benefits of diet change to the user. The more complex data entry requirements facilitate this linking of diet to enteric emissions; however, for many users the level of detail required is a potential barrier to completion. Supporting users to collect more accurate feed data would not only allow more precision in emission assessment but would also allow users to better understand their feed use and enable them to identify opportunities to manage this for improved productivity. For example, feed conversion rate is an important KPI to reduce emissions in livestock systems by enabling farmers to understand where there are inefficiencies in their production processes. To calculate this requires information on the amount feed supplied to the livestock and the weight gain achieved. Calculators that make an assumption on the amount of feed consumed by the livestock are unable to take feed conversion rate into account. Given that at the current time there is a lot of variation among farmers in the level of detail of their farm data, having a flexible approach where the calculator can cater to low and high levels of detail, such as in calculator E, supports a wider range of users.

Monogastric livestock also produce enteric emissions though these are much lower than those for ruminant livestock and IPCC 2019 does not provide factors for poultry due to a lack of robust evidence. When assessing pigs, the calculators did include the enteric emissions. Calculators A, B, C, D and E did not include these emissions for poultry systems whereas calculator F did. Calculator F predates the review by IPCC and draws on a single separate data source (Leip et al., 2010) to provide a value; it is unclear how this value was calculated, and it was not adopted in the IPCC 2019 refinement.

All the calculators currently use GWP100 as their default warming potential for methane (and the other gases); however, with increasing scrutiny of methane there is increasing interest in looking at the shorter-term impact of methane (e.g. GWP*) and the potentials for cooling if sufficient methane emission reductions are achieved, though this requires understanding how methane emissions have changed over time. One calculator (E) provides this functionality necessitating the user to provide 20-year average production data to enable the calculator to make significant assumptions about changes in methane emissions over time. Others are considering how this is included in future assessments.

Fertiliser application emissions from the application of nitrogen to soils differed between the calculators. With the exception of calculator F, there has been a convergence of methodologies around the IPCC 2019 guidelines in recent years, meaning that differences in results have been somewhat reduced. However, importantly, the difference between those using Tier I versus Tier II/III remains. A user of the calculators needs to understand whether a Tier I or II/III approach has been used in the assessment of direct nitrous oxide emissions in order to be able to understand the implications on the emissions in their results. The calculator providers do share with users information on the Tier of calculations used in their calculators.

The IPCC 2019 Tier I method has an aggregated direct nitrous oxide emission factor (1% of nitrogen in the fertiliser lost as nitrous oxide) and three disaggregated values: synthetic (1.6%) or organic (0.6%) nitrogen sources in ‘wet’ climates, and all types of nitrogen input (0.5%) in ‘dry’ climates (where the climate type depends on the ratio of precipitation to evapotranspiration). Research via the UK GHG platform (e.g. Sylvester-Bradley et al., 2015) was used to develop an equation for the UK GHG Inventory that linked average annual rainfall and fertiliser rate to direct nitrous oxide emissions. It is recommended that calculators use an approach that takes into account rainfall (e.g. the UK GHG Inventory emission factor or the IPCC disaggregated emission factors applied in alignment with rainfall conditions). Tier III approaches may allow for additional granularity. It is important that these are used in a way that does not cause confusion for users and instead helps the user to understand how they can manage their system to reduce emissions.

The calculators calculate direct nitrous oxide emissions using different approaches:

- Calculators A and D use the Tier II emission factor aligned with the UK GHG Inventory; this uses the site-specific average annual rainfall to determine the extent of these emissions.
- Calculator F uses IPCC Tier I approach with default emission factors from Bouwman et al. (2002). During the course of the data collection phase, calculator B was calculating direct nitrous oxide emissions using a model based on Bouwman et al. (2002), which took into account site-specific factors including crop type and soil characteristics. Soon after data collection was completed, it moved to using the disaggregated IPCC Tier I emission factors and uses site- and management-specific information to determine whether the ‘wet’ or ‘dry’ emission factor should apply. With an approach that switches between two emission factors based on annual climate data, there is a risk that a minor change in conditions could result in a threshold being reached and the calculator moving from one emission factor to another; this could result in confusion for users who might be managing a crop similarly between years but find that emissions are much higher in one year than another.
- At the time of assessment, calculator E was using the disaggregated IPCC Tier I emission factors and using site- and management-specific practices to determine which should apply (including using monthly weather data to avoid the emission factor choice being sensitive to minor changes between years). It is moving to a Tier III approach that accounts for soil conditions (e.g. pH), which could provide more opportunities for users to understand the factors that impact on these nitrous oxide field emissions.

The functionality of the calculators is such that changes in nitrogen application rate will be reflected in the results, and therefore where farmers are improving nitrogen-use efficiency in the crop and reducing total nitrogen applications, all the calculators will show proportional reductions in both direct and indirect emissions. However, if a farmer seeks to have a more detailed understanding of how they can reduce their emissions or are intending to use the results of the analysis to calculate how close they are to net zero (e.g. for a supplier to collect bonus payments, for calculating the sequestration or removals requirements needed to balance emissions, or for determining surplus removals available for sale), then a higher Tier calculation that incorporates soil, climate and management information would provide a more relevant assessment. For example, using a calculator that captures the impacts of using enhanced efficiency fertilisers (e.g. nitrification inhibitors) would better enable users to account for their use of these products on their emissions or understand their likely impacts if they were to use them. Only some of the calculators incorporate these; this is discussed in the ‘Support for mitigation’ section.

For indirect nitrous oxide emissions resulting from nitrogen lost from the system via volatilisation or leaching/run off, all calculators were using either the IPCC 2006 or IPCC 2019 calculations and emission factors.

The scientific evidence base for nitrous oxide emissions from soilless systems is less robust than for traditional soil-based cropping systems. The lack of soil microbial communities and recirculation of nutrients within hydroponic systems means they behave very differently. For crops such as tomatoes where they are grown in soilless systems, the methodologies used in soil-based systems are not directly transferable. For soilless media growing systems, some studies suggest lower nitrous oxide emissions than the IPCC default values, with a study by Karlowsky et al. (2021) finding that in a German glasshouse producing hydroponic tomatoes and cucumbers with closed hydroponic systems (recirculation), that emission factors were equivalent to 0.31% for tomato and 0.13% for cucumber, compared to the IPCC default value of 1%. The differences between soil and soilless systems mean that in order for these specialist growers to use the calculators they require specialist functionality within the calculators, which was only available in calculator E, with the others assuming the same emissions as a soil-based system. This suggests that users should be aware of where specialist functionality is available within the calculators to enable them to choose the calculator most appropriate to their needs.

Nitrogen is also returned to the soil as ***crop residues*** remaining *in situ* and this results in nitrous oxide emissions. Users are unlikely to know the quantity of residues remaining and, therefore, the calculators will need to determine this. The results of the calculators' assumptions can be seen in the breakdown of emissions for the Cereals 1 model farm. The calculators used the IPCC approach for calculating the production of residues based on relationship between the yield of the crop and the amount of residues (both above- and below-ground), but whereas some used the default parameters from IPCC (e.g. calculator B), others applied Tier II parameters (e.g. A and D use the values from the UK GHG Inventory; this assumes a lower residue yield for many crops than given with IPCC calculations, as it is found the IPCC overestimates residue yield for high-yielding cereal crops in the UK). In some calculators there is the opportunity to modify the crop residue value manually (e.g. B) if the user knows what the residue volume is. There are, however, different approaches taken by the calculators in how they deal with residues removed for baling. One of the calculators (B) removes all emissions from residues if the user selects that residues have been removed, which means that the calculator does not take into account that stubble would be left to release emissions (a workaround approach is provided to enable users to capture these emissions, but the calculator is reviewing the process with the aim of improving it). Other calculators allow the user to select the proportion of total biomass removed from the field (calculator A, with the user guide suggesting when cereal grain and straw are removed, 10% of biomass remains on the field). Calculator E asks for the straw yield and assumes that all other residues remain *in situ*. The result of this is that there are different emissions for the different calculators. Where calculators (such as B) are giving a significant overestimate for residues left in field and underestimate for residues removed for baling, there is a risk that it can encourage behaviours that increase baling and removal of residues in an effort to reduce emissions if the user only looks through a climate change lens at the situation. The return of crop residues may improve soil health and resilience, which may have longer-term climate benefits in the rotation (though it is important to note that there are multiple factors, such as soil type, existing soil organic matter levels, etc., that will determine the impact of additional residue incorporation). Therefore, this potential exaggeration of the difference between removal and incorporation of residues may lead users to be misinformed over the impact of residue removal resulting in less favourable decision making.

Manure emissions were an important contributor to emissions for the dairy systems (as can be seen in the breakdown of emissions for the ***Dairy 1*** model farm), and there was variation in the emissions among the calculators. Understanding what factors are driving these differences was challenging due to some calculators aggregating emissions from manure in housing, stores and on pasture.

When out to pasture, livestock will feed on the pasture while also depositing dung and urine. Farmers will have limited ability to quantify the volume of feed consumed and the volume of manure produced, necessitating the calculators to make assumptions on these volumes. In order to simplify data entry, the majority of the calculators require the user to provide average time at grass within the calculator. In many grazing systems cattle, for example, are housed for part of the year, then may have partial turn out, before going out all day. In dairy systems the milking cows will spend part of their day on yards or in the parlour. Therefore, it can be a complex calculation for the user to make to accurately estimate the actual proportion of time the cattle spend at pasture. This requirement for users to make calculations outside of the calculators means that there is a risk of errors being made in those calculations and different users making different assumptions in similar situations. Where calculators are able to allow greater granularity of data entry, and clear guidance to users on the assumptions that should be made, there is less risk of differences in approach. The quality of the forage can impact on both nitrogen content and digestibility of the forage which has implications for both manure management and enteric emissions. However, in all calculators there was insufficiently detailed information collected on the grazing quality to make anything other than high-level assumptions on the impact of grazing quality on emissions. Where grazing emissions and emissions from the application of manufactured fertilisers or organic manures to pasture are not disaggregated (such as in calculator D) in livestock assessments, this can limit the user's ability to interpret what is driving these emissions and therefore reduces their understanding of where they might target their decarbonisation strategy.

Livestock ***manure management*** is an area where the farmer has many options for controlling emissions and is therefore an area where it is expected that there will be increasing focus in the future with regards to adopting mitigation strategies. Changes in practice will only have relatively small impacts; therefore, to be detected calculators need to have sufficient sensitivity. However, livestock manure management is a complex area with many interlinking pieces with a temporal element as well as point source emissions. A number of gases are released, most importantly ammonia, nitrous oxide and methane. Although ammonia is not a direct GHG, it does contribute to indirect nitrous oxide emissions, and importantly is a serious air pollutant in its own right. Actions that are taken to mitigate GHG emissions need to also consider the implications for ammonia and avoid increases in ammonia emissions as a result of reducing nitrous oxide emissions (i.e. pollution swapping).

In order to fully understand emissions from livestock manure management ideally the calculators would look at housing, storage and application as a linked sequence – with a nitrogen and carbon balance linked to feed intake, calculated from deposition in housing/yards, through the housing, storage and application to ensure that by the time the manure reaches the point of application to land there are appropriate assumptions for its nitrogen content. This is important because if mitigation in housing and storage has been successful there should be higher levels of nitrogen in the manure at application. That higher level of nitrogen in the manure then needs to be accounted for at application; for example, if poor application techniques are used there is the risk that any gains made in storage could be outweighed by losses at application.

Our review of the calculators found that only A, E and F had any sort of nitrogen balance flowing through them. In calculator B it was noted that there was no direct link between the manure that is produced in the livestock enterprise and any manure that is applied to the crops that are assessed (instead a standard nitrogen content of manures is assumed). In this same calculator there was no way of checking that all the manures that were produced in the livestock enterprise were correctly accounted for across the cropped area (either grassland or other crops), and as a result there is the opportunity for a user to miss emissions from application related to the livestock enterprise.

In the whole-farm calculators, there tends to be the assumption that all the manure that is produced on-farm is used on-farm and therefore application emissions are all captured within the whole-farm emission assessment. They do allow the option to export manures and, in that case, the exported manure application emissions fall outside of the farm boundary and are excluded from the total assessment (although given that the importing farm may assume zero embedded emissions for the imported manure, this would mean that any emissions from the temporary storage on the exporting farm are missed from farm-level carbon assessments of both the supplying and receiving farms).

Although these calculators potentially have a link between storage and application, there is limited capacity to account for the nitrogen losses from manure storage in the nutrient content of the applied manures. In order to create more accurate assessments, there is a need to create nitrogen balances that are able to link deposition, storage, application and export. Where sequential management of manures takes place, care must be taken in accounting for losses at the different stages; the IPCC 2019 guidelines provide emission factors for a range of manure management systems, but these emission factors have been considered in isolation and are not necessarily suitable for use in combination where multiple manure management systems have been used (i.e. they are not necessarily additive). The guidelines have the default recommendation of using the emission factors from the dominant system; however, they also suggest that losses can be calculated through combining emission factors by weighting these based on the duration of time the manure spends in each system. Including user-provided data on the nutrient contents of applied manures will enable losses to be better accounted for. Intensive livestock units may be required to comply with Best Available Techniques (BAT) in order to gain environmental permits (GOV.UK, 2023a); as a minimum, the calculators need to provide manure management systems that align with BAT standards.

There are some quite significant differences in the emissions from livestock manures. Some of these differences might lead to users selecting different optimum mitigation strategies depending on the calculator that is chosen. In the IPCC 2019 guidelines, the standard emission factors for emissions from storage manures indicate higher methane and nitrous oxide emissions from slurries (liquid manures) than from farmyard manures (FYM) (solid manures with bedding). There was however one calculator (D), where with the same data entered emissions from FYM were significantly higher than slurry for one model farm. This is contrary to the IPCC guidelines and risks creating confusion in the sector when reviewing management options.

Another difference between the calculators is the level of detail that the user can enter with regards to their manure management system. At the simplest they are just asking if the manure is managed as solid or liquid (A and D, though note that calculator A has now moved to alignment with the management practices in IPCC 2019 guidelines), and the calculator is then making an assumption on management practice and using the same management practice for all farms. Calculators B and E have aligned with the list of manure management options that are available within the IPCC 2019 guidelines, meaning that they are able to be more sensitive to manure management practice. However, even in these calculators the options tend to be "either/or", so you can manage your manure one way or another, but you cannot easily sequentially manage the same manure through different systems, e.g. separating into different types of lagoon and then putting some elements through an anaerobic digestor. Calculator E has additional manure management practices and also has a temporal element linked to frequency of emptying.

At present, the simple nature of the data entry, and the aggregation of the emissions into a single 'manure management' category in the results at best (e.g. calculators A and B) or combination into 'livestock emissions' at worst (e.g. calculator D) means that there is limited functionality within the majority of the calculators to allow users to model and evaluate alternative manure management strategies to support their decision making (and investment) for the future. There is also no explicit information about ammonia emissions, meaning that a user is unable to determine if an action might reduce GHG emissions at the expense of increasing ammonia emissions. For many farms, only a single manure management practice will be used, but as farms look to reduce emissions and make best use of manures, there will be more interest in modelling more complex management systems.

There is currently no functionality within the calculators for some of the in-house management approaches that are being implemented in some pig units such as ammonia scrubbing of ventilation gases or cooling of slurry stores. These actions are predominantly being targeted at ammonia reductions but have the potential to decrease GHG emissions too via reductions in indirect emissions following ammonia volatilisation. In addition, there is a lot of work being done across the industry looking at novel management approaches such as manure separation, collection of methane from stores for use as fuel, acidification of stores, use of nitrification or urease inhibitors in stores and sequential management of manures whereby they go through a series of processes before they are ultimately returned to land as some form of fertiliser.

It is recognised that one of the barriers to the incorporation of these practices into the calculators is a lack of robust evidence and consistent results to demonstrate the scale of emissions reduction that are possible through the implementation of some of the more novel practices that are being considered by the industry. There is a need to apply a significance threshold as to whether farmer uptake of the technology, the extent of its mitigation impact and the quality of the evidence of that impact is sufficient to justify its inclusion in the calculators.

Conclusion: The majority of the calculators are using the IPCC 2019 guidelines as their main method for assessing both nitrous oxide emissions and methane emissions from agricultural systems leading to greater alignment in results than previously might have been the case. However, there remain differences between those that use Tier I or Tier II approaches, and those that attempt to go a little further and adopt aspects of Tier III localised approaches. The more precise and accurate the method, the more granular the data entry required, but also the more granular the results are. The more detailed the approach (e.g. moving to a Tier III approach), provided that it is applied well, the more specifically relevant it is to the user's location and potentially the greater the opportunity for the impacts of more specific mitigation activities to be represented within the results.

Recommendation:

- Consider options to provide greater guidance to the user on the impact of methodology on their results, and the alignment of different methodologies with their needs in creating the emissions assessment.
- Encourage the incorporation of more sophisticated carbon and nitrogen balances within the calculators to account for the impacts of mitigation in one place on the emissions from another.

Land-based carbon removals and emissions

Farming systems, with the exception of some protected horticulture and housed livestock production systems without land, have large carbon stores in the soil and in vegetation. There are two parts to the carbon store: those parts that are in long-term residence, such as elements of the soil carbon and woody biomass in trees, and those that have more transient residence, such as the annual uptake of carbon into plants via photosynthesis and relatively rapid loss via respiration (of plants, animals or microbes). Carbon stores can be in three states: they can be net emitters (sources) if carbon removal is lower than emissions (e.g. where soil carbon is being eroded or woodland removed); they can be in equilibrium (where removals balance emissions – this state is '*assumed'* in the Tier I method of the IPCC for accounting purposes to be reached within about 20 years of a land use or management practice change occurring); or they can be net removers (sinks) if carbon removals exceed emissions. Increasing the carbon store on-farm can help to balance residual emissions produced by the farm; however, this requires that the user can demonstrate permanence and additionality of those carbon removals. Some farms may choose to sell carbon credits/certificates, but that is not discussed in this analysis.

Land-based carbon removals and emissions were considered for a subset of the model farms, and this data demonstrated that very different approaches were being taken by the calculators. The differences result from what is included within the system boundaries of the calculators and the specific approaches that they take to calculate these emissions and removals. The standards that the calculators align to is a factor in these differences. While the older PAS2050 standard excludes land based removals unless resulting from land use change ("Where not arising from land use change...changes in the carbon content of soils including both emissions and removals shall be excluded from the assessment of GHG emissions... unless provided for in supplementary requirements in accordance with [their] principles"), the Greenhouse Gas Protocol and ISO standards require carbon emissions and removals from attributable processes to be included in the assessment if significant, though these need to be reported separately. Consequently, the older PAS2050 does not allow farmers to benefit from practice changes that sequester carbon within a given production system, but only when land use change occurs. In contrast, the GHG Protocol and ISO standards require such changes to be accounted consistently so that both emissions and removals from land management changes are accounted for. Harmonisation will require that calculators move to these recent standards that set out the requirement for the inclusion of land-based carbon removals and emissions.

Above-ground carbon removals can be achieved through planting of trees or hedges, as well as the introduction of perennial crops. The Woodland Carbon Code has been developed in the UK for assessing above ground carbon removals. It was created by Forest Research, part of the Forestry Commission, in 2011 and provides a robust approach to modelling and assessing carbon in a range of woodlands. There is also work in place by the Allerton Project to develop a Hedgerow Carbon Code although that was not available at the time of assessment. However, the calculators all take different approaches to assessment of carbon in trees. As mentioned in the *System Boundaries* section, some calculators only consider trees within the field margins, while others allow woodland to be included. Defining the requirements of a farm-level carbon assessment would help determine what should and should not be considered part of the 'farm' (i.e. should forestry operations or woodland be included) so as to create consistency as to what woodland, hedgerow and boundary trees are included in a farm level carbon assessment.

Calculators C and E align with the Woodland Carbon Code (which is designed to be robust enough to create carbon credits). Calculator E implements a Tier III approach to further disaggregate the Woodland Carbon Code models for greater accuracy. Calculator D uses parts of the Woodland Carbon Code. Others use the area of coniferous vs broadleaved woodland in age brackets and what the previous land use was if not woodland and link this to the IPCC Tier I sequestration calculations (A, B). The use of IPCC approaches means that the analyses are generic at a global level and may not reflect actual rates of growth in UK woodlands and lack much granularity in the data that can be provided on woodland. Utilising Woodland Carbon Code functionality enables greater detail to be included on the yield potential of the woodland. The calculators all tend to assume that the woodland that is present is permanent, and is not destined for harvest or thinning, which can exaggerate the carbon removals where these practices are in place. Asking the user what they intend to use the woodland for would help to determine whether long-term sequestration is occurring.

There is growing interest in agroforestry, such as silvopastoral and silvoarable systems, though the calculators do not have specific modules in the calculators that identify agroforestry (calculator E does have the capability but is currently not used due to lack of user demand). However, where it is possible to select number of trees and density of trees (e.g. E) there is the potential to capture some aspects of agroforestry, but there is often limited scope to clearly define the system, e.g. if a user is using fruit or nut trees they will have different growth rates and final sizes compared to timber trees, such as poplar.

there are a number of the calculators (A, B and F) that use the Tier I land use and land use change guidance in the IPCC guidelines to give an indication of changes in ***soil carbon stocks*** over time and use this to calculate changes in soil carbon following a switch from grassland to arable, or from intensive cultivation to minimum tillage practices, or use of cover crops. The IPCC approach is designed for use at global scale and therefore lacks any real nuance for application at field- or farm-level. It does not take into account details of soil type, existing soil organic carbon or have any sensitivity to different ways practices are implemented – e.g. use of rotational ploughing rather than annual ploughing. This approach takes an average carbon stock in land use X and average stock in land use Y, then looks at the difference between the two, divides by 20 and allocates this as an annual value for either emission or sequestration. It simplifies the complex processes and although it is enough to see that a change in practice has the potential to deliver carbon removals or even emissions, it lacks the sensitivity to provide any accurate quantification of any potential removal or reversals.

The way that this method has been applied in some calculators goes beyond the intention of the Tier I guidance. Whereas the IPCC guidance covers a whole system change (e.g. a 100% ploughed system changing to a 100% minimum tillage system and remaining that way), some calculators (A and F) have used this data to capture carbon stock gains or losses based on fluctuating practices across a rotation.

Calculator E uses the IPCC Tier II steady-state method. This approach takes into account climate, soil and management conditions in order to provide soil carbon stock changes that are more disaggregated than those produced by default Tier I methods.

Note that the UK GHG Inventory assumes that there are no carbon stock changes when moving from conventional to reduced or no till (UK GOV, 2023, p. 899-900); this based on a report that suggests that tillage type does not influence soil carbon stocks in the UK. The IPCC data is based on global averages and is therefore less specifically relevant to UK soils. However, where site-specific data can be collected that supports changes in soil carbon stock (i.e. a Tier III approach) this should be captured within the results. Calculator E uses the IPCC Tier II guidance and a bespoke modelling approach to consider carbon fluxes in more detail, including through location-specific modelling, which could potentially provide clearer understanding of changes in soil carbon. In some calculators, modelling approaches are being complemented with the use of physical measurements made on-farm (e.g. D and E). These calculators can take the field measurements and use this to provide evidence of changes in soil carbon concentration. Using a combination of actual in-field measurement and modelling approaches enables a more robust approach to demonstrating change than just modelling alone, but does require sufficient soil samples, completed correctly (e.g. with bulk density measurements) and recorded correctly, to ensure a fully robust approach. Even in these calculators they can only be accurate on areas of the farm where actual soil carbon data has been collected. In general, data collection on past and present land management practices is limited, which reduces the opportunity to understand across the whole farm what the current storage is and how that might change with current and future land management.

One area of growing importance to the farming sector is the oxidation of drained peat, and the fact that where cultivation is occurring on drained peat, there are significant emissions associated with the losses of carbon from these soils. The UK GHG Inventory uses a default value of 37.17 t CO_2e/ha/year for lowland peat (>40 cm) converted to agriculture (UK GOV, 2023, p. 922). Given that typical emissions for an arable system are 1-2 t CO_2e/ha/year, the inclusion of peat emissions could lead to a 30-times increase in emissions. However, these emissions are inconsistently applied in the calculators. Only calculators D, E and F include these emissions, but they differ in how they do this, from a fixed loss per year (calculator D) to a modelling approach that accounts for peat characteristics and management actions (calculator E). Failure to recognise the impact of cultivating high organic matter soils in a farm-level assessment will underestimate the impact of that particular farming system on the climate, and also obscure key mitigation requirements from the user. This also applies to farming on upland peat.

The way that results are presented in the calculators has the potential to mislead. Removals are sometimes referred to as *stock changes*, sometimes *sequestration* and sometimes, erroneously, *offsets*, which can be confusing.

Removals are also usually presented alongside the emissions data which may lead to the assumption that they have similar levels of accuracy and robustness, and that the user can balance one against the other to calculate a carbon balance. From the evidence that we have seen, in some of the carbon calculators, the carbon removals data provides an indication of whether a practice is likely to lead to an increase in carbon removals or not, but lacks the granularity and detail to robustly quantify the actual scale of removals to a level of rigour that is suitable for truly balancing emissions. Accuracy and sensitivity vary between the calculators due to differing levels of refinement, so it is important to look below the surface calculations of removals and consider the robustness of the method employed to calculate them.

The SBTi FLAG requirements clearly state a need to present emissions and removals separately and align with the GHG Protocol Land Sector and Removals Guidance (still in draft) that requires companies only include carbon dioxide removals with ongoing storage and monitoring data and processes. The ongoing monitoring should be captured in a monitoring plan and that plan needs to be able to demonstrate that the carbon remains stored, and the monitoring approach has to have the potential to detect losses if they were to occur. The reporting of losses and removals must be traceable through to the carbon sink itself (this is possible on-farm). The company must also only report removals *'if the net carbon stock changes are accounted for using empirical data specific to the sinks and pools where the carbon is stored in the company's value chain'.* Removals should be reported if they are statistically significant and the producer is able to provide quantitative uncertainty estimates for the removals value.

While no calculators provide transparent quantitative uncertainty assessments associated with their carbon removals values, calculator D does give a confidence rating to their outputs (with the carbon stock changes rated as 1 out of 3 suggesting low confidence) and the providers of calculator E offer quantitative uncertainty assessment as part of their support package to users. Without uncertainty assessment there is a risk that the user is led to think that they can assume that the level of robustness in these assessments is sufficient to allow them to balance any residual emissions. Where calculators give results for farms that indicate near carbon neutral or even carbon negative values there is the risk that the user will determine that no action is needed to address any emissions, which may drive inappropriate behaviours, especially if there is a risk that the carbon removals calculation is not fully representative of that farm.

There are farmers currently selling, or are looking to sell, carbon credits or certificates from carbon removals on their farms. It is important that those areas of the farm are not included within any whole-farm carbon assessment to avoid double counting. Aligning to a standard that sets out rules that prevent double counting (e.g. ISO 14064:2, which calculator E is aligned to) prevents this from happening.

Conclusion: Carbon removals are complex and influenced by a wide range of factors including soil type, climate, historic management practices and future management practices. Carbon stores are dynamic and therefore snapshot estimates of carbon storage based on data for a single year is insufficient to provide a robust estimate of actual removals. It is therefore important that models have sufficient historical data or valid assumptions regarding land use and management, are sufficiently refined to be sensitive to influential management practices such as tillage and forest management and are able to consider reversals and assure permanence where this is required. Measurement of soil carbon in particular is complex and lacks a standard agreed methodology. Where calculators have aimed to simplify the process, care must be taken to ensure that any simplifications do not prevent them being able them to deliver on the above otherwise they run they risk being inaccurate, imprecise, biased, or insufficiently sensitive to management practise to assure confidence.

Recommendations:

- Consider options to highlight uncertainties – In order for users to robustly balance their residual emissions with carbon removals it is important that the calculators provide an uncertainty analysis of the data that is presented on carbon removals and make it clear to the user what the short comings of the approach are. This point should also extend to measured values of carbon sequestration which may be used to supplement modelled values. If, for example, a farmer inputs measured carbon values, the uncertainty of those measured values should be evaluated based on the method and sampling strategy used, and this uncertainty should be weighed against that of the model.
- Consider options to improve transparency – It is recommended that there is greater granularity presented in the carbon removals data, such that the user understands the difference between removals associated with different parts of the farm, and the differing levels of uncertainty (e.g. woodland vs soil carbon) and robustness, measured vs modelled results.
- Consider developing improved guidance to users on the level of rigour that is needed in assessing carbon removals. The SBTi and GHG Protocol documents are complex and inaccessible to most users. However, they could be distilled into some key messages for farm-based users as to what to look for when using a calculator to support removals calculations. Alignment with guidance in the ISO, SBTi and GHG Protocol standards, will support increased harmonisation in the UK and globally.
- This guidance should also extend to how to deal with carbon credits within the boundary of assessments to ensure that where credits are created and sold outside of the farm the land used to create them is not included within the assessment boundary.
- For consistency, all calculators should be encouraged to reflect the impact of cultivation of peatlands on overall emissions and have a transparent way of displaying those emissions in the results tables (especially as they may dwarf other emissions on-farm). For robustness, all calculators using Tier I approaches for biogenic sources and sinks should seek to move to higher-tier methods.

Support for mitigation

Early carbon calculators were used to create baseline assessments of what emissions were being produced, and from where, within the system. Increasingly, they are being used to monitor change and determine whether a farm or enterprise is reducing emissions over time, or to model how those reductions might be achieved. If farmers are being measured on their ability to reduce absolute emissions through the use of these calculators, it is important that the calculators are able to recognise how changes in on-farm practice will impact emissions. Being able to capture these beneficial mitigation practices in the carbon assessment can incentivise the uptake of these practices (provided that supply chains recognise this).

To be able to monitor those changes, it is important that the calculators have the functionality to be able to allow the user to capture the mitigation activities they are practicing and determine the impact. This could be a case of the calculator having sufficient options for the user to select the option that matches what has been done on-farm (e.g. if they have used certified deforestation-free soya then having that option for selection within the feed list). For other mitigation practices (e.g. using nitrification inhibitors), the calculator will only need to know whether the practice is used or not, and if it is used, an emission factor can be applied in the calculations. In other cases, mitigation practices can be more complex where management practices interact with multiple components within the calculation, for example the responsiveness of enteric fermentation calculations to changes in diet.

As enteric methane and nitrous oxide emissions are two of the most significant sources of emissions on-farm, there will be increasing focus within the agriculture sector in developing mitigation practices that tackle these. Reducing enteric fermentation emissions, already discussed in some detail above, is of key importance to dairy, beef and sheep producers. Key areas where farmers can address enteric emissions are through:

- **Livestock numbers** – Increasing productivity of the system can enable a reduction in livestock numbers while maintaining or increasing output. Reducing livestock numbers is well addressed in the calculators, with users able to adjust livestock numbers to reflect their situation. Guidance to support users in accurate entry of data on livestock numbers, for those calculators who currently do not offer this, would improve this further. Some calculators provide KPIs (e.g. milk yield per cow, calving percentage) to help support improved productivity.
- **Changes to composition of animal diet** (increasing digestibility e.g. through increasing fat or starch content) – In a simple scenario model completed using four of the calculators, a beef animal was fed either a wheat only or grass silage only diet at either 5 kg DMI/day or 10 kg DMI/day (this was designed to test function not reflect actual feeding). It was found that calculator A gave the same enteric emissions for all diets, calculator D gave the same emissions for both wheat and silage, but did have increased emissions where higher volumes were fed, and the others were able to respond to both changes in the composition of the diet and the volume fed (calculators B and E). Where calculator A gave no response to the composition of the diet, it did have a separate area in the calculator where the user could modify the digestibility of the diet; this function partially balances out the lack of responsiveness to dietary components, but there is a risk the user might not complete it either because they fail to recognise its importance, or because they do not have the data. From the scenario analysis, it appears that although all the calculators are all using the Tier II approach, the assumptions they are using to support it are different, and their responsiveness to user data entry differs. At their most simple it would appear that the calculators are assuming a standard digestibility of the diet (unless specifically modified by the user) and responding to livestock numbers and size. The intermediate approach seems to link livestock numbers, size and volume fed, but still have a standard digestibility for the diet, whilst the most sophisticated of the three is capturing the individual digestibility of the dietary components to make a more responsive calculation. When it comes to using these calculators for mitigation, having increased granularity of data entry and responsiveness to that data entry will enable users to investigate how dietary change might impact on enteric emissions.
- **Use of methane inhibitors** – This is a relatively new approach that is being investigated by the sector. There are a number of different methane inhibitors on the market, with different levels of evidence to support their claims around methane reduction. At the time of assessment two calculators (A and E) had included functionality within their assessments to enable the user to select methane inhibitors. However, it is important that there is a sufficiently robust process in place to ensure that there is sufficient evidence to support any mitigation factor or equation that is incorporated in the calculator. Until recently, the lack of use of these inhibitors by users and the limited field experiment data available has meant that there has been limited need for the inclusion of these. Given the high level of interest in the use of these inhibitors and the growing evidence base of their efficacy, there is considerable value in their inclusion in calculators and it is expected more calculators will incorporate this functionality.

Nitrous oxide and methane emissions from manure management are the next major areas of interest across all livestock systems. Manure management is a continuum from deposition in housing (or at grass) through storage to application. In order to address emissions from manure management, it is important that there is an understanding of the nutrient content of the manure that is produced, and how that changes over time as the manure moves from house to store, through the storage process and eventually to the field. Although there was evidence in some of the calculators of a partial nutrient balance, it did not appear that any of the calculators had a complete balance through the whole system. The level of granularity available in the manure management sections of the calculators was limited. None of the main calculators had any detail on how manures were managed in-house nor any mitigation options available for management of manures in housing (e.g. frequency of scraping in slurry systems, use of air scrubbers in pig housing). For the management of the manure out of the house in two of the whole farm calculators, the options for manure management were very simplistic – limited to slurry or farmyard manure (D), with some ability to have daily spread (A). However, calculators B and E had more sophisticated management options (e.g. aligned with management types identified in the IPCC 2019 guidance). These management options enable practices such as covering slurry tanks, or use of anaerobic digestion to be captured and the calculator's emissions are responsive to those changes. Calculator E also included a separate module to consider anaerobic digestion in greater detail. In calculator B there was functionality to incorporate manure/slurry at application and again the calculations responded to this, but in A and D there was just the ability to apply manure. In the IPCC guidelines and UK GHG Inventory approaches there is a link between dietary nitrogen, nitrogen content of manures, management practices in house and storage and the resultant nitrogen content of manures applied back to land. There is then additional functionality that modifies emissions from land, based on method of application and timing of incorporation after application. The calculators had a disconnect between these three elements and therefore have limited responsiveness across the whole system to support increased mitigation of emissions within the manure management process.

Given that manure management is one of the key areas of control that intensive cattle, indoor pig and poultry producers have over emissions, it is important that there are sufficient levers with a high degree of granularity within the calculators for them to be able to demonstrate the benefits of practices. This is particularly important as many of the practices and technologies will require significant capital investment to implement. For some of the management practices, such as frequency of scraping, covering of slurry stores, incorporation timing after application, there are datasets within the UK GHG Inventory that have been developed to facilitate these calculations. However, there are a number of new technologies that are being trialled in a range of livestock systems such as methane capture, slurry separation, slurry cooling, slurry acidification and novel application techniques, for which there is no value in the UK GHG Inventory. For some of these there is good evidence for the impact on both ammonia and indirect nitrous oxide as well as direct nitrous oxide emissions, whilst for others there is less clearcut evidence from which to develop emission factors and methodologies for inclusion in a calculator. However, it will become increasingly important that calculators have the ability to rapidly incorporate new technologies into their methodologies to support users in recognising the benefits of these novel approaches.

The calculators varied greatly in what mitigation practices they include. As an example, enhanced efficiency fertilisers offer the potential to reduce nitrous oxide emissions from manufactured and organic fertiliser use, but only some calculators offer these as an option for users. Calculator B includes nitrification inhibitors, while calculator E includes nitrification and urease inhibitors and controlled-release fertilisers. The inclusion of these practices within calculators enables a user to better estimate their emissions and understand the potential emissions reductions these technologies can deliver. Given that these additives cost money, being able to demonstrate a beneficial impact from their use will incentivise uptake of these. Other calculators are looking at including nitrification inhibitors in future versions. It is important to note that the mitigation impact of these types of products is variable (ADAS, 2022); therefore, as more data becomes available through field experiments, these emission factors and how they are applied in the calculators should be updated.

Conclusion: As users move from assessing baseline emissions to wanting to identify and quantify the impact of adopting mitigation practices such as novel feeding approaches, new manure management systems, use of inhibitors and novel fertilisers, it becomes increasingly important that calculators are able to quantify the impact of adopting these practices. However, it is also important that there is a robust process in place and clear guidelines available for the incorporation of new technologies into calculators to ensure that the emissions reductions that are captured are genuine.

Recommendations:

- Consider the development of a clear and robust pathway for enhancing mitigation functionality within the calculators (that is transparent).
- Consider options to improve granularity of manure management pathways and feeding pathways to enhance functionality and responsiveness to change on farm.
- Consider options to work with industry to support funding of primary research to develop the evidence base at a UK level for some of these practices, especially where there are complex interactions across the carbon or nitrogen cycles.
- Consider options to increase granularity of outputs and results from calculators, even if it is in a secondary set of images to support the user in developing improved and targeted mitigation programs.

Discussion

This report has captured a snapshot of the results of the calculators using the versions that were available at the end of May 2023. Due to the developing nature of the science and the regular updating and refinement of the guidance (particularly in relation to SBTi and GHG Protocol Land Sector and Removals), the calculators are updated at varying frequencies, with a number of major updates delivered across the lifespan of this project and a number of other major changes expected to occur later in 2023. Therefore, it is expected that some of the points of difference identified in this analysis will have been addressed before it is published, whilst other points of difference may also arise after publication. However, it is important to support users in recognising that development of new functionality and updates to methodologies should not be a barrier to uptake, as these new functions and methods are made available to older assessments and should not fundamentally change the targets for mitigation.

The reasons for the current wide variation in the results have been explored in the previous section. We have aimed to present the findings in a way that enables the results from this analysis and the recommendations for the future to remain valid, even as the exact make-up of the individual calculators changes over time.

Comparing results from 20 model farms

It is clear from the analysis of the data from 20 model farms that the different calculators are taking different approaches to assessing emissions and removals. No models are perfect or identical in all aspects, therefore some variability due to the approach taken is to be expected. It is not as simple as the calculator with the highest or lowest value is better or worse than another. It is important that the user understands what is and is not included with the calculation when looking at the results (e.g. are capital items in or out, and how is land-use change captured in embedded feed emissions), and to what extent these boundaries are aligned with the latest carbon standards. For some embedded emission factors, e.g. for feed, fertilisers, and energy, the most up-to-date reference databases should be used. The user should also be able to obtain an understanding of how assumptions have been built into the calculations, the frequency with which emission factors are updated (and therefore their current relevance) as well as understanding what data they need and do not need for the assessment that they are creating. Variability due to inaccurate user input data should be avoided wherever possible, and calculators should provide support to users to ensure entry of high-quality data.

Data entry

The calculators are generally designed to be applicable to a range of farm types and user requirements. For this reason, they are not designed to constrain a user to a specific assessment approach, and some are limited in how they define the scope or boundaries of the assessment to the user. Farms are complex businesses, that often comprise of non-farming enterprises as well as the crop or livestock production. These might include woodland or forestry, or diversification activities such as camping sites, storage facilities, Bed and Breakfast, etc. These may be critical to the farm income, but are not part of the agricultural enterprise, and they may also utilise land or resources that are shared by the farming enterprise making it challenging to separate. For this reason, there is the need for users of these calculators to have some understanding of what they are trying to achieve and therefore what they should be assessing before they commence data collection. However, where the user is an individual farmer, this knowledge may not be present, meaning there is opportunity for incorrect or inconsistent data entry approaches, or even fear of getting it wrong that prevents farmer users from getting started. It tends to be easier for farmers and calculators to define boundaries in simpler systems, e.g. single enterprises like egg or poultry meat production, than in complex multi-enterprise or diversified farms.

At present, all calculators, with the exception of B and E, predominantly work on an *honesty system* that assumes that a user is honest in entering the data; however, there is a risk that where there are financial implications (e.g. a bonus for demonstrating emissions reduction, or link to public goods payments) that the user could choose to misrepresent the system in order to improve their emissions results. For example, where there is an option to select if soya is certified deforestation-free, or fertilisers are inhibited, that the user selects those options without actually having undertaken the practice, thus gaming the system. Such results would not be acceptable to carbon reporting standards such as ISO or GHG Protocol, since any misleading data would not fulfil their criteria of being *Complete, Representative, and Accurate*. Calculator E requires users to upload evidence that practices are in place as required by ISO14064:2, whilst calculator C gathers user specific external data and verifies that data before the assessment is completed. In other cases where data from calculators without this functionality is being used for supply chains or for financial payments there may be a requirement for external data validation.

There are instances where calculators have been designed to provide a simple user interface that is accessible to an uninformed user, but these tend to face the challenge of how to convert simple input data into more complex calculations. This tends to result in those calculators having to make a series of standardised calculations, which means that the results from the analysis can be fairly generic, and the user lacks the ability to capture specific management practices and have those influence the results. However, there is value in these calculators as a starting point for a user to understand the main sources of emissions on their farm; this approach can enable a user to begin to take action to reduce their emissions without the barriers that more complex calculators might create (e.g. barriers to engagement due to the data requirements or complexity of data output). However, there are more sophisticated calculators available such as calculator E that have worked to develop user interfaces that facilitate both complex data collection and ease of use. Other calculators are in the process of moving towards more sophisticated user interfaces but had not completed the transition at the time of assessment. The original platforms could be complex and confusing to the non-expert user.

Support on data entry is available at different levels for the calculators. Some provide validation of the data (e.g. to determine whether it falls within expected parameters), others have support services to walk users through data entry, the majority have user guides of differing levels of clarity, whilst others also have help buttons that pop up while using the calculator. All these features support the user in understanding better how to use the functionality in that particular calculator. Greater use of these techniques across the different calculators, especially data validation at entry, and increased focus on making the guides useful to the farming audience will support improved accuracy of data entry. With greater complexity of data requirements, more support is expected to be needed by non-expert users to ensure that data entry is accurate. This will be particularly important for farmers who have barriers to the use of carbon calculators including being time-poor, those who are less technologically literate, and those that do not have, or only have poor, access to the Internet.

Though the study was not intended to test the ‘usability’ of the calculators and no specific assessment was made of that, in the process of data input it was identified that there was the potential for increased use of automated data validation (e.g. highlighting abnormally high or low values) in the calculators. One calculator did provide combined DMI per head for livestock, or total nitrogen application rate, which could be useful when entering data for multiple feeds or fertilisers, but there was still a lack of guidance of whether the user values fell within an expected range. An element of human validation has been required for most calculators in the past. However, the use of artificial intelligence and machine learning has recently been adopted by calculator E to identify potentially incorrect data, demonstrating how newer technologies could increase the sophistication and accuracy of data entry. The accuracy of the carbon assessment is only as accurate as the data that is used to calculate it, therefore increased focus on data checking and validation at point of data entry will support greater accuracy of carbon assessments.

Where the calculators can connect to farm data management software, this can be both timesaving and also reduce the risk of incorrect data entry in the carbon calculator (assuming that data has been entered correctly into the management software in the first place). There are a number of the calculators that have developed APIs (Application Programming Interfaces) with other software packages to enable transfer of data. This functionality was not tested as part of the analysis.

Data outputs

One factor that stood out in the calculators was the inconsistency in how the data outputs are presented. The majority presented the emissions broken down by the constituent gases (methane, nitrous oxide and carbon dioxide) and then converted those into carbon dioxide equivalents. However, they split those emissions up into different levels of aggregation. The simpler the presentation of the results (i.e. the more they are grouped together into fewer categories) the more difficult it is for a user to identify where they can take action to reduce emissions or enhance removals. However, the more complex and disaggregated the presentation of results, the more risk there is of confusion and lack of understanding of what they mean. Different standards have different reporting requirements, and at present the way the results are presented in some of the calculators does not always support the way companies or organisations need to report their emissions, for example by scope (as per GHG Protocol standards). There is increasing interest in methane emissions and transparency of those especially in light of the global methane pledge that aims to reduce global methane emissions by 30% from 2020 levels by 2030, therefore being able to clearly identify total methane emissions becomes increasingly important.

The calculators all report GWP100, which is the reference global warming potential used in national inventories for the main gases released via agricultural systems. However, the transient nature of methane in the atmosphere has resulted in other models for methane emissions being developed such as GWP* and the agriculture sector has shown great interest in this. Only calculator E (at the time of assessment) offered the possibility to assess against both GWP100 and GWP*. It is important to remember that whatever approach is taken to presenting results from methane, it needs to be possible to track reductions in the quantity that is produced to ensure that the right practices are in place to minimise methane emissions in the future and support the efforts to create global cooling. If the adoption of GWP* results in farmers thinking they need not take any action, there will be a missed opportunity for tackling climate change.

Supporting the move to Net Zero

The main drive behind GHG emission and carbon removal assessment is to support corporate, national and international targets to decarbonise the agricultural and food system in a shift to Net Zero. Carbon calculators have a role in determining baseline data, and provided they contain sufficient levels of granularity in data collection, mitigation practices and clarity of output, there is an opportunity for the calculators to be used as decision-support tools to help identify opportunities for mitigation, and also monitor progress towards targets and goals linked to reducing the climate impact of agriculture.

Additional functionality in the calculators, such as the ability to benchmark against peers, can support this process, but there needs to be a robust validation process in place to ensure data entry is accurate and the results are a true reflection of the practices. It is possible to benchmark assessments completed within a calculator, but at present the divergence in approaches for data entry, calculation and presentation of results means that it is not appropriate to benchmark between assessments completed in different calculators. The benchmarking process can help identify where individual farms are doing well compared to others and where there is room for improvement. For example, calculator A provides product-level emissions benchmarking against data collected from all users of the calculator; this is for overall product emissions and for individual emission source categories. Note that where benchmarking is being provided by calculators, this tends to be at a product level; product-level carbon assessments were not included in this project. Given that product-level assessments are calculated on a per quantity of output basis, year-to-year variation in weather and other factors outside the farmer’s control that impact on production will influence the product-level emissions, even when the farmer is managing the system in a consistent manner. This needs to be taken into account when benchmarking. Where the farmer has multiple years of data, benchmarking may be more informative when using an average value taken over multiple years. With increasing benchmarking data, it may be possible to identify the specific mitigation practices that enable some farms to have lower emissions than others. It is important in benchmarking that there is some understanding of the dataset that is being compared against. For example, how old are the assessments, is there any process for updating or removing old assessments, what definitions of farm type are used to compare one to another. Comparison to old assessments with old emission factors and practices may distort the current picture of where an assessment sits in the UK landscape. The calculators present an opportunity to model the impact of decisions (for the future) to help farmers plan for the most appropriate practices to implement. However, it is rarely seen that this capability is well utilised; greater training and support to users may be required to encourage this approach to decision making. Some calculators are encompassing decision-support function, guiding farmers into actions that can support reduced emissions. Calculator E provides an ‘Optimisation journey’ to enable identification of practices that can reduce emissions or increase removals; this also includes typical costs for actions enabling a cost-benefit assessment to be made by the user. Calculator E also provides scenario planning within the carbon calculation module, and a ‘Scientific Benchmarking’ functionality, where users' results may be benchmarked against dynamic datasets designed to reflect the farm's own possible best practice. Calculator C offers multi-group benchmarking, scenario planning footprints and action planning complemented with expert advice. There is, however, a limit to what the calculators can do and these need to be complemented with expert advice (e.g. through effective knowledge exchange activities). Calculator E provides free connection to a new generation digital engagement and collaboration platform for knowledge development, knowledge exchange, and upskilling.

For Net Zero calculations it is important that calculators are presenting carbon removals (whilst taking into account additionality, permanence and leakage). However, the lack of a single agreed methodology for assessing carbon removals (especially below ground removals), means that different approaches have been taken to provide a ‘number’. Several of the calculators use the Tier I mineral soil carbon stock change methodology from IPCC, which is not the same as carbon removals. Calculator E is the only calculator to follow a Tier II methodology for this calculation. The robustness of the assessments and the uncertainty associated with them is not transparently presented in all cases (where it is available users may have to specifically request it), leading to the risk that users place greater weight on the outcomes than is justified.

Where there are high levels of removals (sequestration or offsets are used to describe these in the calculators) calculated by the calculator, but a lack of data is collected on permanence, there is the risk users think they need take no action to reduce emissions, and potentially misses the opportunity for mitigation of emissions to take place. In contrast, presenting carbon sequestration as a negative emission is appropriate and aligned with the latest carbon standards (with PAS 2050 too, but this protocol omits many important sources of carbon sequestration since it only allows for consideration of carbon stock emissions and removals associated with land use change, so will be of limited value in assessing approaches to Net Zero).

Alongside changing farm systems to mitigate climate impacts, there will be a need for farm systems to change in order to cope with the impacts of climate change. Flooding, drought, changing pest pressures and other impacts from climate change will make some systems unviable in their current locations without changes. The project did not include within its scope consideration of how these calculators can support adaptation strategies, but this is an area where calculators should support farmers in their decision making.

The harmonisation of carbon accounting will ensure a calculator's results are comparable, or 'fungible', enabling farmers to efficiently and rigorously evaluate land use options and farming practices, which is vital for an efficient and successful move towards Net Zero. An added benefit of this is that it will enable fair flow of additional economic incentives provided by the nascent burgeoning carbon credit markets. Carbon credits and the wider concept of natural capital were out-of-scope for this project; however, these are growing in importance, and carbon calculators have a role to play in carbon and natural capital markets. Should calculator providers wish to align their calculators with these markets, they may be required to follow standards that are additional to those presented in the recommendations in this report. For example, BSI's BS 8632:2021 Natural Capital Accounting standard.

Harmonisation

The introduction of the Net Zero legislation and increased interest in farm-level carbon accounting has resulted in increased use of carbon calculators and increased recognition that the calculators are not harmonised in the approaches that they are taking and the outputs that they are providing.

Given that some calculators were using out-of-date emission factors and calculations, a key priority for improving harmonisation is to ensure that all calculators have a process in place to ensure that they are regularly updated.

Should a harmonised approach be required, the most logical way would be through the creation of an agreed UK baseline standard. This could take the form of a set of agricultural-specific guidelines building on, for example, the GHG Protocol and ISO standards, which provide clarification where there is room for interpretation in the current guidelines, covering calculations, emission factors and data requirements. This baseline standard would determine which IPCC emissions factors, emission factor databases, global warming potentials and calculations should be used in harmonised calculators for farm-level emission assessment. It would then be a choice for the calculator providers whether to align with this.

This approach would not necessarily define the specific calculations to use. This would create a burden on whoever develops these guidelines as they would have to take on responsibility for determining the most appropriate calculations and sourcing relevant emission factors. There are potentially common calculations that are available for calculators to use (e.g. the methane and nitrous oxide calculations from the UK's GHG Inventory.

It is clear that the different calculators are producing different results for different reasons. The level of precision and the amount of functionality in the calculators are responsible for some of that difference. Pragmatic approaches have been taken where the amount of data and the level of precision required by the calculators is balanced against the benefit that it would provide to improved accuracy of emission quantification. Increasing data requirements might place a bigger burden on users and in some cases the users may not readily have access to the required information; however, calculators can provide approximations to enable this increased functionality rather than excluding this completely due to challenges in data collection. Better data collection and integration with data management systems should enable greater levels of detail to be collected by the calculators. One source of variability identified in this analysis was that increasing specificity of emission assessment (e.g. moving from Tier I to Tier II or III approaches) can improve accuracy but also requires more data and creates other opportunities for divergence (e.g. if calculators use different rainfall data for the calculation of nitrous oxide emissions from soils).

Full harmonisation of carbon calculators is unlikely to be possible to achieve without risking elements of intellectual property; however, it is important that there is a set of minimum standards or guidelines that are specific to farm-level carbon assessments against which calculators can align. As the calculators continue to develop, they are moving beyond the publicly-available methodologies and creating their own evidence-based approaches. Nevertheless, alignment with the latest global standards such as ISOs 14064 and

14067, and the GHG Protocol Land Sector and Removals guidance (for SBTi FLAG) should be a minimum requirement.

Where farm-level assessments are feeding into product footprints, the differences in results between the calculators creates a challenge for quantifying Scope 3 emissions for supply chains. There is a risk that suppliers are attracted to the calculator that provides the lowest value for their supply chain; however, unless the calculator is compliant with the latest carbon footprinting standards, which consider carbon emissions and removals associated with land management change, the outputs will not be admissible for carbon footprinting and SBTi. This has implications for product ecolabelling as consumers may make purchase decisions based on the carbon footprint provided for the product; if different methodologies are used in the product-level carbon assessment of different products, the ecolabels on these products may not be comparable. This includes consideration of how the product-level carbon assessments take into account year-to-year variation in yield performance (i.e. does it capture emissions for average performance or is it a snapshot of a single year of data). Product-level carbon assessments and ecolabelling go beyond the scope of this project, but they are being considered by the Food Data Transparency Partnership; this is investigating how to improve the availability, quality and comparability of data in the food supply chain in order to support improved environmental sustainability (GOV.UK, 2023b).

In the meantime, increasing transparency of the approaches currently taken and their limitations will support informed choice of approach for users. Transparency over the approach taken for selection and maintenance of emission factors will also support increased accuracy of calculators as they recognise the need to update and refresh emission factors.

Conclusions and recommendations

In order to start the process of decarbonisation on farm, one of the first steps is to understand where the main sources of emissions are from a particular farm and its combination of enterprises. This is done through the assessment of emissions and removals and is facilitated via the use of a carbon calculator designed for use in agriculture. Defra have identified that one of the barriers to uptake of carbon assessments is that farmers do not know which calculators to use as each calculator gives different answers. There is a lack of understanding in the sector that as the results are modelled there is no single 'right' answer. However, increasing harmonisation of the calculators so that there is a more consistent approach to what is included in a farm level carbon assessment, the calculation of emissions, emissions factors used and presentation of results, aims to support farmers in recognising those calculators that are aligned with this harmonised approach, whilst still allowing for innovation in the carbon calculator sector.

This review of the calculators focused on the divergence between them, rather than areas of consistency to look at how harmonisation can be achieved. These are the key conclusions.

- All calculators provided a useful assessment of baseline GHG emissions from farms, with most working to align with the IPCC 2019 methodology and emissions factors (although at the time of assessment not all had completed this transition). Despite this there were areas of difference that resulted in divergence of emissions results. When carbon removals were considered, there was a greater level of divergence in approach, with a number of calculators using a carbon stock approach aligned to IPCC land use change methodologies, whilst others employ more sophisticated carbon removals approaches.
- A user needs to be clear why they are completing a farm level carbon assessment (or be told why they are completing the assessment) in order to be able to determine what is included in their assessment. Farms are complex businesses that often comprise non-farming enterprises as well as the crop or livestock production. These might include forestry, or diversification activities such as camping sites, storage facilities, bed and breakfast, etc. These may be critical to the farm income but are not part of the agricultural enterprise; they may also utilise land or resources that are shared by the farming enterprise making it challenging to separate. Therefore, when completing a farm-level carbon assessment it is important that the user knows what should and should not be included.
- There are standards and guidance available to support GHG emission assessment – such as the ISO 14064 and 14067 GHG standards, GHG Protocol Land Sector and Removals guidance and Science Based Targets FLAG guidance. However, none of these are specifically targeted at farmers, or farm-level carbon accounting. They are more generic in nature or aimed at larger supply chains and therefore leave areas of assessments open to interpretation when applying to farm-level carbon accounting.
- GHG emissions assessment and carbon removals are an ever-evolving science. This is clearly shown by the changes in the IPCC guidance and factors over time, but also by the demands of industry and farmers to incorporate new technologies and practices into the calculators. Robust processes are therefore required to determine when and how frequently calculators update to align with new science and guidance. Across the duration of the project, and in the period since the analysis was complete, the

calculators have gone through a process of significant change, with large investments being made to update methodologies, improve emissions factors and create better functionality. It is anticipated that as the science develops the calculators will continue to invest and improve their functionality. Since the data collection phase of this project, there have been major updates to a number of the calculators (particularly around updating emission factors), which will have reduced the differences in the farm-level emissions for some farms. Further updates are planned. Conversely, there has also been divergence in places as individual calculators have incorporated new features to better capture detail on mitigation actions, though this will have had less impact on the differences between the calculators.

- A key area of weakness in the calculation of emissions from beef and sheep systems in particular (but it did affect some dairy, pig and poultry systems) was a lack of embedded emissions from purchased livestock being included in the calculators. This is complex as there are many different ways of producing the stock and ages at which they are purchased, so a single standard emission factor is not practical. In addition the way that livestock numbers are captured in the calculators tends to oversimplify what is happening, so working to improve the accuracy of the livestock inventory in the calculators would support increased harmonisation as farmers will be able to more accurately enter their own data.
- Calculators that collect greater granularity of data from users provide outputs more specific to the farm. For example, where calculators that have more UK-specific nitrous oxide emissions calculations (Tier II or III) and link to UK weather data, they are able to more accurately reflect nitrous oxide emissions than those that use generic IPCC emission factors that are applied at a global level (Tier I). Those calculators that have robust carbon and nitrogen balances flowing through the modelling will enable more specific estimation of emissions for a particular UK farm than those without or with only some of these features.
- The calculators vary in their level of detail and the mitigation options that they model. For example there are differing levels of inclusion of methane inhibitors, nitrification inhibitors, novel manure management approaches and the opportunity for including user-specific emission factors (e.g. specific fertiliser or feed manufacturers' published and validated emission factors). Where there are higher levels of detail and mitigation options, users are better able to understand where there are opportunities to reduce emissions and their mitigation actions will be reflected in their carbon footprint.
- Carbon removals and emissions from land management activities such as cultivation of peatlands were the areas that saw greatest levels of divergence across the calculators. In part this was due to a lack of consistent agreed methodologies for assessment and also due to limitations in data collection within the calculators. Cultivation and farming on lowland peat is a potentially significant source of emissions in a farming operation. That these emissions were only captured in some calculators and not all has the potential to mislead farmers on these soil types into failing to recognise the peatland itself as a major source of emissions.
- Having the ability to understand how others in their peer group have delivered emission reductions without negative impacts on productivity will support uptake of best practice. This means that the infrastructure supporting the calculator, e.g. benchmarking, user guidance and other support, can be as important as the calculator itself in supporting change.
- Although this project only considered farm-level emissions, where product-level level emissions can be assessed in these calculators, these will also show a high level of difference. This has implications for Scope 3 emission accounting in supply chains as it may encourage suppliers to select the calculator that provides the lowest emissions, rather than the most accurate or relevant assessment. The report did not explicitly consider challenges unique to product-level footprints, but it was noted that where the assessed calculators provided product-level outputs, these were potentially skewed by how the calculators considered rotation-level data (e.g. frequency of liming or manure applications).

Recommendations

In order to support on-farm carbon assessment as part of the process of decarbonisation, it is important that farmers and the supply chain have confidence in the scientific authority of the approach and understand to which standards it is delivering. The current level of divergence between calculators can, in some cases, be extensive. Addressing this through a focus on the use of latest standards and protocols, full representation of a farm's activities, guidance on emissions and removals, increasing functionality through greater data granularity, and maintenance of up-to-date emission factors, will increase user and industry confidence, increase relevance to the user's farm, and efficiently advance the process of decarbonisation.

When aiming to harmonise farm-level emissions assessment, it is important to define first why an assessment is being made, what it is trying to measure, and who the output is for. It is recommended that there is a clear agreement developed within the industry as to why farmers should be completing farm-level emissions assessments (as opposed to individual product-level assessments), in order to create clear guidance of what should and should not be included.

The creation of '*standard farm-level guidance'* that links to the global standards (GHG Protocol standards, ISO carbon footprinting standards and SBTi FLAG guidelines) but interprets in a consistent way how they should be implemented at the farm level (including enterprise and sector specific guidance), could support consistent interpretation and enable calculators to harmonise their approach. Alongside supporting greater clarity of what is meant by a farm-level carbon assessment, this guidance should provide general recommendations for the agricultural sector, such as what emission factor databases to use, while enterprise-specific guidance can address specific challenges, such as how to deal with embedded emissions from purchased livestock. Improved guidance on a standardised approach to assessing and quantifying carbon removals in soils, vegetation and from land use changes, will support greater harmonisation of approaches in calculators around carbon removals. This should, for example, include a requirement to include emissions from peat soils. It is important that guidance includes requirements for the level of rigour and evidence needed to support removals claims, reflecting the importance of permanence, additionality, saturation and leakage in understanding of removals along with estimates of uncertainty.

This guidance should include recommendations for standard reference databases for embedded emissions (e.g. energy and fuel, feed and fertilisers), and where calculators are accessing bespoke values calculated by feed or fertiliser manufacturers, provide guidance on the minimum standards that should be applied in the creation of those factors. For example, where the manufacturer of a compound feed is using generic emission factors for its ingredients to create an overall carbon footprint for the feed product, ensure that it is using the same database as being used by the calculator (e.g. both are using the GLFI). Using standardised values will further enhance harmonisation. Also, include within the guidance a standardised approach to dealing with embedded emissions in purchased livestock, where specific data is not available.

The methodologies and emissions factors used in carbon accounting are being refined and updated, and new technologies to mitigate climate change impacts are being developed. Carbon calculators need to be able to review these developments and rapidly update existing methodologies or deploy new methodologies to be aligned with the latest science and research, but need to have a transparent approach to communicating with users how they are aligning, the frequency of updates and the current stage of alignment.

Where assessments are being made linked to Net Zero it is important that carbon removals (rather than carbon stock changes) are assessed. At the time of writing the GHG Protocol Land Sector and Removals Guidance was in draft, but it aims to provide greater clarity on how carbon removals should be accounted for. There would be increased consistency in the calculators if they aligned to this guidance once it is finalised. At least one calculator was already aligned with the draft guidance. This guidance includes requirements for the level of rigour and evidence needed to support removals claims, reflecting the importance of permanence, additionality, saturation, and leakage in understanding of removals along with estimates of uncertainty. Where farm specific detail is needed this should be captured in the 'standard farm-level guidance' mentioned above to ensure consistent interpretation at the UK farm level.

Calculator providers have tended to be led by the data that farmers already possess no matter how limited, often simplifying data collection. Augmentation of farmer data with additional data sources (e.g. spatial), and with connections to existing systems (e.g. API connections to farm management software) can mitigate this simplification. Greater granularity of input data was found in the analysis to lead to greater responsiveness of the calculator outputs to changes in practice. For example, greater detail of feed allocation to cattle meant that enteric methane calculations were more responsive to dietary changes. Where data was collected at herd level there was less evidence of results changing in response to data entry. Therefore, it is recommended that calculators aim to allow greater granularity of data entry in areas where the largest emissions are seen, while simplifying data entry in areas where climate impact is less significant (in cases where simplification is a user requirement). Supporting and incentivising users to collect more specific data (e.g. on livestock weights and feed usage) would allow better quality calculator outputs. It could also provide data for driving better decision making and productivity, creating a 'win-win' situation of reduced emissions and improved financial performance.

To support the industry to understand and discuss carbon assessments more easily, it would be beneficial for the development of recommended emissions categories and reporting standards (separation of gases, Scopes 1, 2 and 3). These emissions categories could include, for example, embedded emissions from manufactured fertiliser production; nitrous oxide from manufactured fertiliser application, organic matter application and residue returns (as three separate categories), enteric fermentation, and methane and nitrous oxide emissions from manure in housing, storage and application.

Even with guidelines to bring about harmonisation, some difference is likely to always remain between calculators; these do not necessarily reflect the accuracy of the calculators, but can instead result from the calculators having to make assumptions in order to model these complex systems and because the calculators differ in the functionality that they provide. It will be important to support users to identify the calculator that provides the right level of standards, functionality and precision for their needs and enable them to generate data that can drive practical actions for reducing emissions and increasing removals. Alongside this, it is important to recognise that the more informed the user is, the more value and accuracy they will gain from a farm-level carbon assessment, and therefore there remains a need for knowledge transfer to upskill the industry to understand how to decarbonise and improve their understanding of carbon accounting.

Recommendations

Our recommendations for supporting the harmonisation of farm-level carbon accounting are:

1. Industry and HMG to clearly define what a farm-level assessment is, how it is going to be used, and what parts of a farm business should and should not be included.
2. Calculators to align with the requirements of the latest standards and guidance – currently GHG Protocol standards (including the upcoming Land Sector and Removals guidance) and ISO 14064 and 14067. Industry and HMG to provide guidelines to support a standardized way of applying these in an agricultural context.
3. Calculator providers to regularly review and update calculators to account for changes in scientific knowledge, carbon accounting methodologies and new emission factors.
4. Calculator to comply with the latest IPCC guidance (currently IPCC 2019) and use those calculations and emission factors as defaults where Tier I approaches are used. Where appropriate, calculators to use Tier II and Tier III calculations where robust emission factors and methodologies are available, such as emission factors created for the UK GHG Inventory.
5. Calculators to use emission factors from an agreed set of robust databases for embedded emissions in fertilisers, feeds and fuels. Industry to support the development of appropriate emission factors for embedded emissions in purchased livestock.
6. Calculators to present outputs in compliance with the latest standards. Industry and HMG to define consistent disaggregated output categories for use by all calculators to facilitate understanding of emission sources.
7. Calculator providers to build user confidence through transparency of approach and third-party verification of the alignment of calculators to minimum standards.

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Disclaimer

ADAS have previous and existing relationships with some of the calculators assessed as part of this project, providing support in improving functionality and methodologies. We do not commercially benefit from the success or failure of any specific calculator and remain independent of the calculators.

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