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I. Leinonen, V. Eory, M. MacLeod, A. Sykes, K. Glenk and R. Rees
Scotland's Rural College, Kings Buildings, West Mains Road, Edinburgh EH9 3JG

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Executive summary

Background

The Climate Change (Emissions Reduction Targets) (Scotland) Bill, amending the Climate Change (Scotland) Act 2009, set the ambitious GHG emissions reduction targets of 90% by 2050, compared to a 1990 baseline. In accordance to this, the Climate Change Plan (Scottish Government 2018a) set out policies aiming to provide further GHG mitigation in Scotland's non-emission-trading sectors, including agriculture. Encouraging farm-level carbon audits is recognised as one method to achieve this. Here we compared available farm carbon audit tools to assess their potential application in Scottish agriculture.

Key findings

- 64 potentially applicable tools were identified through a web search. Of these, nine were selected for more detailed comparison. Analysis found that a further six were not suitable due to a variety of shortcomings (e.g. general purpose of the tool, major limitations in comprehensiveness, lack of transparency).
- We have concluded that only three of those tools would be suitable for farm level carbon audits in Scotland:
    a. AgRE Calc
    b. Cool Farm Tool and
    c. Solagro (JRC) Carbon Calculator
- They follow a similar calculation framework (international guidelines and international calculating standards), although none can be judged to be fully comprehensive. Although currently free to use, maintenance and development of the carbon audit framework requires continuing investment. In addition, their application needs to be embedded in wider environmental and farm

context in the form of advisory support (i.e. the tool should not be the sole information source for decision).

- The comprehensiveness and practicality of each tool varies between production systems (e.g. crop production, livestock production, carbon sequestration). No tool is fully comprehensive, and each can only handle a limited amount of possible emissions reductions on farms. None of the three recommended tools considers embedded emissions in livestock bought in.

Recommendations

Of the total of 64 farm-level carbon accounting tools identified in the initial search, We recommend three tools to be considered for a potential roll-out of carbon audits in Scotland on the grounds that they are scientifically robust, comprehensive and practical: 1) AgRE Calc, 2) Cool Farm Tool, and 3) Solagro (JRC) Carbon Calculator.

This research did identify some variations in the comprehensiveness and practicality of different tools. For example, the level of detail in the emission calculations from different sources are not the same, nor is their ability to estimate mitigation from various management practices. Nevertheless, further development to resolve some of these issues is ongoing, and improved versions are expected.

In case of a national level roll-out of any tool, there may be merit in some public investment to tailor tools better to policy needs (e.g. using existing government datasets, benchmarking results).

Contents

Glossary

Embedded livestock emissions: Emissions that are associated to the livestock production chain but are occurring outside the farm in question, including for example emissions from suckler cows in beef production, sows in pig production and breeder birds in broiler production.

GHG emissions: Emissions of greenhouse gases to atmosphere, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride.

IPCC: The Intergovernmental Panel on Climate Change, United Nations body for assessing the science related to climate change. https://www.ipcc.ch/

LCA: Life Cycle Assessment, a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Specified in international standards: https://www.iso.org/standard/37456.html

Tier 1 Methodology: IPCC methodology for assessing GHG emissions, based on simplified default emissions factors.

Tier 2 Methodology: IPCC methodology for assessing GHG emissions, based on more detailed, country-specific emission factors.

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1. Introduction and Background

The Climate Change (Emissions Reduction Targets) (Scotland) Bill, amending the Climate Change (Scotland) Act 2009, set the ambitious GHG emissions reduction targets of 90% by 2050, compared to a 1990 baseline, with the longer term view of setting a net-zero emissions target year. The GHG emissions from agriculture and related land use were 10 Mt CO_2 equivalent in 2016, which is about 26% of the total GHG emissions in Scotland (Scottish Government 2018b), and the opportunities agriculture and wider land use can offer in GHG mitigation and carbon sequestration (Eory et al. 2015) are key determinants of climate policy. In accordance to this, the Climate Change Plan (Scottish Government 2018a) set out policies aiming to provide further GHG mitigation in Scotland's non-emission-trading sectors, including agriculture.

One of these policies is the encouragement of farm carbon audits as a way to encourage the wider uptake of best practices in GHG emission reduction on farms. While dozens of farm level sustainability assessment tools exists (de Olde et al. 2016), the number of tools suitable for carbon audit is much smaller. With the expansion of sustainability assessment tools, including farm-level carbon calculators, the need for their evaluation has emerged (Binder et al. 2010, Marchand et al. 2014). Multiple carbon audit tool evaluations so far (Hall et al. 2010, Keller et al. 2014, Lewis et al. 2012, Sykes et al. 2017, Whittaker et al. 2013) have mainly concentrated on user friendliness and application rate of the tools (and not so much on the technical structure, scientific assumptions and background data used in the tools), or have limited the analysis to one or only a few production systems.

The objective of this project was to compare available farm carbon audit tools and to assess their potential application in Scottish agriculture.

2. Methodology

The comparison of the tools in this study was carried out as a four-step procedure.

1. A web search was carried out to identify all available tools that have been used/can be used for farm-level GHG accounting.
2. All potentially suitable tools were evaluated against specific criteria (see Annex 1) to be selected for a more detailed assessment.
3. After the exclusion of unsuitable tools, a final shortlist of was created.
4. For the tools considered suitable for farm level carbon audits in Scotland, a detailed assessment was carried out, based on final evaluation criteria (see Annex 1 and Annex 2).

3. Results

We found a total of 64 potentially applicable tools through a web search. After the first evaluation nine tools were considered in more detail. Further six tools were excluded for reasons which became clear only after this more detailed investigation. Finally, we found that three tools fulfil all criteria needed to be suitable for farm level carbon audits. The recommended tools are AgRE Calc, Cool Farm Tool and Solagro (JRC) Carbon Calculator.

These three tools mainly follow a similar calculation framework in quantifying the GHG emissions, namely the IPCC guidelines and international standards for life cycle assessment (LCA). Although all these tools can capture a variety of sources of farm level GHG emissions, none of these tools can be considered to be fully comprehensive. The comprehensiveness and practicality of each tool varies between production systems. For example some tools are better than other in covering the emissions from crop production or specific livestock systems, and handling the carbon sequestration.

The applicability (comprehensiveness, practicality and scientific robustness) of the three recommended tools can be summarised as follows:

AgRE Calc:

Coverage: The tool covers all main agricultural production systems in Scotland. The emissions associated with crops include embedded emissions from fertiliser production and pesticides, carbon dioxide emissions from application of urea and lime, direct nitrous oxide emissions from synthetic and organic fertiliser use and crop residues, and indirect emissions from fertiliser application as a result of volatilisation, leaching and runoff. The emissions associated with livestock include those embedded in feed, methane from enteric fermentation and nitrous oxide and methane from emissions from manure management. This tool does not take into account the embedded emission from brought-in animals (see Glossary for definition).

Robustness: The calculations are mainly based on scientifically approved IPCC Tier 2 methodology. The embedded emissions from different livestock feed items (a total 64 items) are mainly taken from the Dutch FeedPrint calculator (http://webapplicaties.wur.nl/software/feedprintNL/index.asp). The feed (and nitrogen) intake is calculated based on the type of the animal, body weight growth rate etc. Biomass carbon sequestration is based on the forested area.

Practicality: In crop production, the farm activities with potential GHG mitigation effect that can be assessed with the tool include reduction in fertiliser use (but not changing the type of synthetic fertiliser), fuel use in field operations, and improvement in yield (affecting per-unit GHG emissions). In livestock production, the embedded feed GHG emissions can be affected through changes in the feed composition (if known) and through the total feed consumption (affected e.g. by animal performance). The changes in the manure management system have direct effects on the emissions through system-specific emission factors.

Ownership: AgRE Calc is a commercial service owned and developed by SAC Commercial Ltd, the commercial holding company of SRUC. SRUC provides individual farmers in Scotland free access to the tool for auditing their own businesses but reserve the right to agree charges for other uses of the tool.

Cool Farm Tool:

Coverage: The tool covers all main agricultural production systems in Scotland. However, it is only possible to assess one production system each time, not the whole farm, even if there would be several production systems at the same farm. The emissions associated with crop production (carbon dioxide, nitrous oxide and methane) include those arising from fertiliser production, induced by fertiliser use, and soil carbon losses (and carbon sequestration); these result from management and land use changes, crop residue management, pesticide production, biomass changes and changes in soil carbon stocks. The emissions associated with livestock include emissions embedded in feed, emission from enteric fermentation and emissions from manure management. The users can calculate their own carbon footprint for home-grown feed. The tool does not take into account the embedded emissions from brought-in animals. The electricity and fuel use are based on user input data. Alternatively, in crop production the fuel use can be estimated by the tool based on default fuel consumption of field operations.

Robustness: Cool Farm Tool applies a detailed method for calculation of soil GHG emissions, and goes beyond the IPCC Tier 1 and Tier 2 methods, including indirect and direct nitrous oxide emissions, embedded emissions form mineral fertilisers and changes in soil carbon stock. The soil emissions are affected by factors such as application rate, fertiliser type, crop type and soil properties. All livestock modules make use of Tier 2 approach for manure management, i.e. specific nitrogen excretion factors and volatile solids amounts are calculated based on the feed intake. However, for livestock categories other than cattle, the emission calculations use a very simplistic approach, which allows very little input from the user and is mostly based on default values of animal performance. The feed intake is always an input that can be given by the user and the emissions from housing and manure management are directly affected by the actual feed consumption data, according to IPCC Tier 2 calculations. The embedded feed emissions are mainly based on FeedPrint (Dutch) data and include emissions from direct land use change.

Practicality: The farm activities with potential GHG mitigation effect that can be assessed with the tool include in crop production the reduction of total fertiliser use, the change between different types of fertilisers, fuel use in field operations, improvement in yield and the change between different crop production systems. With the exception of cattle production, changes in animal performance (through other mechanism than feed intake) have very little effect on the emissions, since the performance is not part of the inputs given by the user. The changes in the manure management system have direct effects on the emissions through system-specific emission factors.

Ownership: The Cool Farm Tool is owned by the Cool Farm Alliance Community Interest Company, a not for profit membership organisation, with members drawn from the private sector, NGO's and research organisations. The tool was originally established as a collaborative project between The University of Aberdeen, The Sustainable Food Lab and Unilever. Over the years the Cool Farm Tool has received many public funding grants such as from the research councils, mostly in partnership with academic members.

Solagro (JRC) Carbon Calculator:

Coverage: This tool can be considered to be the most comprehensive of all tools evaluated here. The calculated emissions include nitrous oxide for the following sources: direct emissions from chemical nitrogen fertilizer applications, manure applications to agricultural soils, crop residues (i.e. leguminous) and grazing / pasture. Indirect nitrous oxide emissions include the following: ammonia depositions on soils and leaching / run-off of nitrates to water. The (embedded) nitrous oxide emissions form processing of inputs include chemical and mineral fertilizers, feedstuffs for animals and buildings and machinery. Methane emissions include enteric fermentation, manure management (housing and storage) and burnt crop residues. Carbon dioxide emissions include direct farm emissions (diesel fuels, other fuels) and indirect energy emissions (electricity) and other indirect emissions (inputs processing: fertilisers, feedstuffs, machinery). It also includes changes in carbon stocks, driven by management changes (e.g. crops <-> grasslands) and trees, hedges permanent crops and agroforestry on the farms. Renewable energy is also taken into account to capture offsetting of emissions. Unlike the others, this tool also considers hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride emissions from cooling storage, machinery, cooling buildings and transport. Like other tools, the embedded emissions from brought-in animals are not included. All main European crop species are covered by the tool, including the main crops grown in Scotland, and the main livestock species are included.

Robustness: For emissions from crop production, this tool applies a relatively simple approach for nitrous oxide (soil) emissions, based on the IPCC (2006) Guidelines for National Greenhouse Gas Inventories. Direct nitrous oxide emissions from organic fertilisers depend on the amount of animal manure, sewage sludge, compost, other organic amendments applied to soils. Direct emissions from crop residues are crop-specific and calculated using IPCC emission factors. Methane and nitrous oxide emissions from burning of the residues are also taken into account. Emissions from drained and managed organic soils are included in the calculations. The calculations of indirect nitrous oxide emissions are based on nitrogen balance at the farm level. The assessment of GHG emissions from enteric fermentation is based on the 2006 IPCC

Tier 2 simplified method for all livestock categories. The amount of nitrogen excreted by the animals is based on IPCC Tier 1 emission factors (i.e. it is constant amount specific for each animal category and not affected by feed intake or feed composition), unlike in the case of other tools evaluated here.

Practicality: The tool has default emission data for 17 single feed ingredients (which is considerably fewer than in some other tools in this comparison), and 35 categories of compound feed (a limited number of these is available for each livestock species). Direct land use change emission (e.g. from soya production) are not taken into account. Changes in soil carbon content are affected by changes in land use and management, and are calculated based on IPCC land use and land management factors. Carbon storage in natural elements is considered. In addition to the calculated, GHG emission, the tool shows up to 16 mitigation or sequestration actions that are used to quantify potential mitigations of GHG emissions.

Ownership: The Carbon Calculator was financed by EU and is freely available. It was first a demand from the COMAGRI (European Parliament) to get a carbon tool at farm level. Then, the DG Environment asked the JRC to launch a public call of tender and Solagro was selected to develop the tool. The tool is currently managed by Solagro.

Table1. Comprehensiveness and practicality of the tools: farm practices that are expected to affect (reduce or increase) the GHG emissions and that can (y) or cannot (n) be assessed using different tools

	AgRE Calc	Cool Farm Tool	Solagro
Crops			
- Increasing yield	y	y	y
- Changing the amount of synthetic fertilisers	y	y	y
- Changing the type of synthetic fertiliser	n[1]	y	y
- Using / changing the amount of organic fertilisers	y	y	y
- Reducing fuel consumption	y	y	y
- Changing management, e.g. tillage	n	y	y
- Increasing woodland area	y	y	y
- Managing the woodland	n	y	y
Livestock			
- Changes in feeding: embedded emissions	y	y	y
- Changes in feed consumption: manure N_2O emissions	y/n[2]	y	n
- Feed emissions: direct land use change (e.g. soya)	n	y	n
- Changes in feed composition: manure N_2O emissions	y/n[3]	y	n

- Changes in feeding: methane emissions	y	y	y
- Changes in animal performance: manure emissions	y	y/n[4]	y
- Changing manure management system	y	y	y
- Herd structure (embedded emissions of brought-in animals)	n	n	n
- Reducing fuel and electricity consumption in livestock housing	y	y	y

1 Only urea has different emission factors compared to other synthetic fertilisers

2 Feed consumption is estimated by the tool, not based on real data

3 Not included in the current web version

4 Very limited information on animal performance (apart from cattle) can be used as input.

4. Discussion

All three tools selected for the final comparison (AgRE Calc, Cool Farm Tool, Solagro Carbon Calculator) use scientifically robust methodologies. There are many differences in the level of detail in the calculations and the general approach used, but each of the methodological choices can be considered scientifically correct.

They follow the IPCC guidance (in most case the detailed Tier 2 approach) for calculating GHG emission, and their framework is based on the international standards for cradle-to-gate LCA methodologies (with certain variations). High scientific standards can also be found in some other shortlisted tools (i.e. GLEAM-i, EX-ACT and CCAFS-MOT), in addition to selected for the final comparison. However, each was developed for other purposes (e.g. regional assessments), so were not very capable of handling farm data, and therefore not suitable for farm-level carbon audits.

Because all three tools use a similar framework to calculate farm level emissions, there are not huge differences in the comprehensiveness of the tools either, and the mitigation methods that might be assessed by the tools are largely similar (Table 1). However, some differences exist, and the most important of those are also highlighted in Table 1.

The GHG emissions from crop production are described in a most comprehensive way in Cool Farm Tool, and the Solagro Calculator has also a relatively detailed crop module. In AgRE Calc, the options to assess the effects of crop management practices are more limited, e.g. it is not possible to distinguish between different types of mineral fertilisers, and options for assessing potential carbon sequestration are also rather limited.

There are more fundamental differences between the tools when livestock production is considered. Probably the biggest difference is related to the relationship between feed (nutrient) intake and the nitrous oxide emissions from housing and manure management (dependent on nitrogen excretion). In Cool Farm Tool, the feed intake is always given by the user (although in some cases calculated default values can be used). In contrast, in AgRE Calc, the calculation of the emissions is based on feed intake that is estimated on the basis of the type of animals and their performance. Of these three tools, the Solagro calculator is an extreme case where the nitrogen excretion is a constant depending only on the type of the animal (Tier 1 approach), and cannot be affected by management. Also other aspects in the animal performance and overall livestock data are taken into account in a different way in different tools. AgRE Calc can utilise a relatively detailed livestock data, e.g. average body weight and growth rate. In contrast, Cool Farm Tool applies very simple inputs for other livestock except cattle, so the animal performance is largely based on default values and cannot be specified by the user.

Change in livestock feed composition is a potentially powerful mitigation option. However, the estimated outcomes of such changes depend on the data used for embedded emissions from different feed items. It seems that the three tools use different data sources for this purpose, and therefore are expected to give very different responses to livestock diet changes. In the Solagro calculator, there is a very limited amount of different feed items the user can choose from, and their embedded emissions are based on a French database. Cool Farm Tool and AgRE Calc both use Dutch FeedPrint data. In addition, Cool Farm Tool can estimate the GHG emissions for home grown feed items if crop specific data are provided to its crop module. One big question concerning the embedded feed emissions is whether or not the emissions related to direct land use changes are included. This is especially critical for soya bean meal. Soya can be considered in calculations either very environmentally friendly or unfriendly, depending on the inclusion of land use change emissions. Of the tools compared here, Cool Farm Tool seems to include land use change emission while AgRE Calc seems not to include them.

Some shortcomings were identified in each of the tools. However, further development to resolve some of these issues is on-going. The Excel version of AgRE Calc includes already other environmental and economic indicators than the GHG emissions (which are currently the only outputs included in the web-based version). Furthermore, the livestock modules of AgRE Calc are currently under further development, and future versions would allow better utilising the actual feed consumption data. A more detailed livestock module for non-ruminants is also under development in Cool Farm Tool. Improvements to the user friendly web-based tools are dependent on future funding.

5. Policy implications

Promoting an on-farm greenhouse gas emissions calculator in Scotland at a national level would have several benefits regardless of which tool is selected. Using a single tool would make the audits comparable across a large number of Scottish farms, and allow a crude upscaling to national level with potential for harmonisation with the national GHG inventory. It would also provide industry-wide credibility to Scottish agriculture, and there is evidence to suggest that industry actors are ready to use such tools. Some of the tools evaluated here are already used worldwide (Cool Farm Tool), or can potentially be used European-wide (the Solagro Calculator); their use would technically allow international comparison for emissions from Scottish agriculture. Further development of the tools would allow also comparison of other environmental and economic sustainability indicators than just GHG. These features already exist in the Excel version of AgRE Calc.

The tools evaluated here also have certain limitations. None is fully comprehensive, and they can only handle a limited amount of possible emissions reductions on farms. For example, soil carbon sequestration is not represented in AgRE Calc. None of the three recommended tools considers embedded emissions in livestock bought in. For this reason, the farmers cannot affect their emission by selecting the origin the animals they buy, or consider possible improvements in the breeding methods. Furthermore, Cool Farm Tool provides only product-specific results, not combined results for the whole farm emissions.

In their present form (in publicly available versions), the tools do not consider other environmental aspects in detail, which might result in key trade-offs being overlooked in decisions based on the outcomes of the tools. It should be also noted that investment will be required for maintenance and further development of the tools. For example, continued harmonisation with the national GHG inventory, implementation of novel mitigation options, building in new evidence, links to new datasets, responding to users' needs, data extraction and analysis are some aspects the cost of which needs to be considered.

In conclusion, it is important to keep in mind that the output of a carbon tool should not be the sole information source for decision making, because that could divert focus from possible solutions not represented in the tool. Instead, the tools need to be embedded in wider environmental and farm context in the form of advisory support.

6. Recommendations

- The tool selected for national carbon audit purposes should be transparent and/or properly documented.
- It is important to consider the comprehensiveness of the tool, including the level of detail of the inputs the user can enter to the tool.
- User-friendliness is an important property, but it should be noticed that this can compromise comprehensives; the tool should not be over-simplified.
- The tools need to be embedded in wider environmental and farm context in the form of advisory support.
- The tool should not be the sole information source for decision making.

7. References

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Annex 1. Methodological framework

The comparison of the tools in this study was carried out as a four-step procedure. First, web search was carried out (using Web of Science and Google) to identify all available tools that have been used/can be used for farm-level GHG accounting. The search strings and the number of articles/websites found are given in table A1. Due to the large number of websites found in the Google searches, only 100 first findings for each search were checked to find potential candidate tools. As a result of the searches, a total of 64 potentially suitable tools were found. All these tools were assessed based on initial evaluation criteria:

1) Availability of documentation,
2) Targeted agro-ecosystem,
3) Suitability for farm level assessment,
4) Applicability to main farm types in Scotland, and
5) Availability of information on implementation.

Of these tools, nine were selected for a more detailed assessment. After an initial analysis, it became quite clear that of these nine tools, there are some that cannot be used for farm-level carbon audits. There reasons for this were the following:

1) The tool will not be made available for audits,
2) The tool has been developed for a different purpose and therefore it is not suitable for farm level GHG assessment,
3) There are major limitations in comprehensiveness, i.e. the tool omits certain significant GHG emissions from the calculations, and
4) The tool is not transparent, so the scientific robustness and comprehensiveness cannot be assessed.

It was considered that failure to meet any of these criteria will make a tool inappropriate for the carbon audit purposes. For the same reason, numeric scoring of the tools was not considered to be appropriate: in addition to being subjective, the scoring could give misleading results for tools that are generally “good”, but fail to meet some critical criteria, such as suitability of their general purpose. Based on this comparison and exclusion of unsuitable tools, three tools were remaining for the final step of the analysis, and for these, a deeper, very detailed evaluation was carried out against the following evaluation criteria.

1) General purpose,
2) Transparency,
3) Scientific robustness,
3) Comprehensiveness,
4) Range of applicability,

5) Practicality,
6) Format of information provided,
7) Legal aspects, and
8) Repeatability.

The tools considered suitable for farm level carbon audits in Scotland were

1) AgRE Calc,
2) Cool Farm Tool, and
3) Solagro (JRC) Carbon Calculator.

For the shortlisted tools not included in the final step of comparison (GLEAM-i, Farm Carbon Calculator, CALM, EX-ACT, IMPACCT, CCAFS-MOT), reasons for exclusion are explained and a brief statement for each evaluation criterion is provided in Annex 2.

Table A1. Results of the web searches of the GHG calculators

Web of Science	**3,803**	**TS=**((*farm* OR agriculture*) AND (carbon OR greenhouse gas OR GHG) AND (tool OR calculator OR accounting OR footprint* OR benchmark*))
Web of Science	1,195	TS=((*farm* OR agriculture*) AND (carbon OR greenhouse gas OR GHG) AND (tool OR calculator))
Google	6	(*farm* OR agriculture*) (carbon OR greenhouse gas OR GHG) (tool OR calculator)
Google	5,390,000	farm carbon calculator
Google	10,300,000	farm greenhouse gas calculator
Google	768,000	farm GHG calculator
Google	34,900,000	farm carbon tool
Google	30,000,000	farm greenhouse gas tool
Google	4,520,000	farm GHG tool

Table A2. Outcome of the shortlisting of the tools

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
AgRE Calc	Not documented but tool fully transparent	Crops and livestock	Suitable	Applicable	Available			Shortlisted
CALM	Likely not available	Crops and livestock	Suitable	Applicable	Likely available	Registration needed		Shortlisted
Cool Farm Tool	Documented and publications available	Crop and livestock systems	Suitable	Applicable	Available	Free software available, registration needed		Shortlisted
Farm Carbon Calculator	Data sources well documented	Crop and livestock systems	Suitable	Likely applicable	Available	Registration needed, free software available	Originally CFF carbon calculator (Farm Carbon Cutting Toolkit community)	Shortlisted
IMPACCT	Some documentation available	Crop and livestock production	Suitable	Applicable	Available	Free software available	EU funded farm GHG tool	Shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
JRC Carbon Calculator	Documented, publication available	European crops and livestock	Suitable	Likely applicable	Tested, results published	Publicly available, registration needed	Funded by JRC	Shortlisted
EX-Ante Carbon balance Tool (EX-ACT)	Available	Crop and livestock production	Suitable	Likely applicable	Information available (publications etc.)		FAO	Shortlisted
CCAFS-MOT	Available + transparent excel tool	Crop and livestock production	Suitable	Technically applicable	Publications available	Relatively high-level tool	University of Aberdeen	Shortlisted
GLEAM-i	Fully documented	Livestock systems	Technically suitable	All livestock systems	Available		FAO	Shortlisted
SAEM	Documentation available	Main livestock and crop systems	Technically suitable, more a research tool	Applicable	Publications available		Based on GLEAM, modified for Scotland	Not shortlisted
CPLANv0 calculator						Could not be evaluated		Not shortlisted
CPLANv2 calculator						Could not be evaluated		Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
Bonsucro calculator	Not known	Sugar cane only	Likely suitable	Not applicable	Not known	Software not available		Not shortlisted
Palm GHG	Some documentation available	Palm oil production only	Likely suitable	Not applicable	Not known	Free software available		Not shortlisted
CCalC	Some documentation available	Technically applicable for any product chains but not specifically designed for agriculture	Technically suitable	Technically applicable but not ideal	Likely available		General carbon footprinting tool	Not shortlisted
Teagasc/Bord Bia Farm Carbon Navigator	Not known	Irish dairy and beef production (access to Irish database needed)	Suitable	Likely not applicable	Likely available		Information tool for farmers, not comprehensive GHG accounting tool	Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
AHDB Carbon footprinting decision support tool	Not documented but tool fully transparent	Cereals and rapeseed only	Suitable	Arable farms only	Not known		Crops	Not shortlisted
CARBON CALCULATOR TOOL v1.5.0	Not known	Not applicable for agriculture (tool for windfarm planning)	Not suitable	Not applicable	Not known		Scottish Government tool for windfarm developmen t	Not shortlisted
COMET-Farm	Not known	Livestock, arable and agrofrestry	Suitable	No, USA specific data only	Not known		USDA	Not shortlisted
COMET Planner	Not known	Livestock, arable and agrofrestry	Suitable	No, USA specific data only	Not known			Not shortlisted
CarbonID™ Calculator	Not available	Arable only, fuel use only	Suitable	Arable only	Not known			Not shortlisted
Vegetable Carbon Calculator	Not documented	Australian Vegetable production only	Suitable	Not applicable	Not known	Registration needed	Not yet available?	Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
The Poultry Carbon Footprint Calculation Tool (PCFCT)	Not documented	USA poultry farms	Suitable	Possibly, but poultry only	Not implemented yet	Tool not yet publicly available	Not yet available?	Not shortlisted
Tesco carbon footprint calculator	Not documented	Possibly	Possibly	Possibly	Not known		Not publicly available?	Not shortlisted
ISR's Cotton Greenhouse Gas Calculator	Not documented	Cotton	Not known	Not applicable	Not known	Link at website not working	Not publicly available	Not shortlisted
Australian Dairy Carbon Calculator – DGAS	Transparent tool available	Dairy	Suitable	Yes, dairy production, (with modification)	Not known			Not shortlisted
Pig Production Environment al Footprint Calculator (PPFEC)	Documented	USA pig farming	Suitable	Pig Farms only: possibly limited applicability in Scotland	Not known	Free software available		Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
Farming Enterprise Greenhouse Gas Emissions Calculator	Not known	Most farm types	Suitable	No, Queensland (Australia) only	Not known	Very high level calculator, just for overview	Australia	Not shortlisted
Carbon Footprint Tool for Milk	Documented	Dairy only (Denmark)	Suitable	Dairy farms only, possibly applicable in Scotland	Likely available	Not freely available	2.-0 LCA consultants, not freely available	Not shortlisted
US Cropland Greenhouse Gas Calculator	Not known	USA cropland, limited crops	Suitable	Not applicable	Not known			Not shortlisted
BovIS carbon footprint calculator	Possibly available	Northern Irland dairy	Suitable	Dairy farms only, possibly applicable in Scotland	Not known	Access needs registration	Northern Irland, dairy	Not shortlisted
Farm Energy Analysis Tool (FEAT)	Documented	Crops, and dairy	Suitable	Arable and dairy farms, potentially applicable	Available	Free software available		Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
Greenhouse Accounting Frameworks (GAF)	Tools fully transparent	Australian dairy, beef, sheep and arable	Suitable	Dairy, beef, sheep and arable, possibly applicable in Scotland	Likely available	Free software available		Not shortlisted
PigGas	Some documentation available, tool fully transparent	Australian pig production	Suitable	Pig farms only, possibly applicable in Scotland	Likely available	Free software available		Not shortlisted
Annual Nutrient Cycle Assessment	Not known	Dairy farms in Holland	Suitable	Dairy farms only, likely not applicable in Scotland	Likely available		Online tool for Dutch dairy farmers	Not shortlisted
FarmGAS Calculator ST and Financial Tool	Not known	Austrarian farms	Likely suitable	Not known	Not known	Not available without registration		Not shortlisted
Holos	Several publications available	Main Canadian farming systems	Suitable	Possibly applicable in Scotland	Available	Free software available	Canada	Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
eFoodPrint ENV	Likely not	Spanish farming systems	not known	Likely not applicable	Not known	Commercial software, not freely available		Not shortlisted
Alltech Dairy 'What If?' Tool	Not known	Dairy, beef, lamb	Likely suitable	Dairy, beef and sheep farms	not known	Registration needed		Not shortlisted
Fieldprint® Platform	Likely not available	USA crop production	Suitable	Likely not applicable	Likely available	Registration needed		Not shortlisted
TropiC Farm Tool	Not known	Crop and livestock production (tropical)	Suitable	Not likely	Not known	Registration needed		Not shortlisted
Sainsbury farm carbon tool	Likely not	Crop and livestock production	Suitable	Likely applicable	Likely available	Not publicly available	Developed by Ab-Agri	Not shortlisted
MiLA	Not known	Crop production only	Not known	Not known	Not known	Registration needed, website in German	Cropping	Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
GHGFarm	Documented	Crop and livestock, applies Canadian emission factors	Suitable	Likely not very applicable	Not known	Not publicly available?		Not shortlisted
Greenhouse gas footprint-tool for Dairy Crest Direct	Not known	Dairy only	Suitable	Possibly applicable	Not known	Not publicly available	Developed by Centre for sustainable Energy	Not shortlisted
The Farm Smart™ System	Not known	U.S.A. dairy only	Suitable	Likely not applicable	Not known	Not publicly available	Developed by Innovation Center for U.S. Dairy	Not shortlisted
FeedPrint	Documentation available	Livestock feed only	Suitable	Applicable for livestock farms (with limitations)	Likely available	Free software available	Developed by WUR	Not shortlisted
OVERSEER	Documentation available	New Zealand farm nutrient dynamics (crops and livestock)	Suitable	Likely not applicable	Available	Registration needed		Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
Carbon Calculator for New Zealand Agriculture and Horticulture	Documented	New Zealand crops and livestock	Suitable	Likely not applicable	Not known	Weblink not working	Developed by AERU and AgriLINK	Not shortlisted
Confronting Climate Change (CCC)	Not known	Fruit and wine production	Likely suitable	Not applicable	Not known	Registration needed	South Africa	Not shortlisted
Orchard Carbon Calculator	Not known	Australian orchards	Likely suitable	Not applicable	Not known	Registration needed	Australia	Not shortlisted
Australian Wine Carbon Calculator	Transparent Excel tool	Australian wine production	Suitable	Not applicable	Not known	Free software available	Australia	Not shortlisted
COLE (Carbon OnLine Estimator)	Some documentation available	Forestry (USA) only	Not suitable (carbon inventory tool)	Not applicable	Likely available		Forestry, USA	Not shortlisted
U.S. Forest Carbon Calculation Tool (CCT)	Documentation available	Forestry (USA) only	Not suitable (carbon inventory tool)	Not applicable	Not known		Forestry, USA	Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
FVS	Not known		Suitable	Not applicable	Not known		Forestry, USA	Not shortlisted
CTCC	Some documentation available	Forestry (USA) only	Not suitable (single tree level)	Not applicable	Not known		Forestry, USA	Not shortlisted
Illinois Farm Sustainability Calculator	Documented, transparent tool	Crops and livestock	Suitable	Likely not applicable	Not known		USA	Not shortlisted
Muntons Carbon Footprint Calculator	Not documented, not very transparent	Cereals only	Suitable	Arable (cereal) only	Likely not available		Barley	Not shortlisted
Cranfield Agri-LCI model	Partly documented	Crops and livestock	Not suitable without modifications	Applicable	Publications available	Not freely available		Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
Carbon Trust Carbon Footprint Calculator	Likely not available	Technically applicable for any products (but unlikely able to quantify agricultural emissions)	Technically suitable	Applicable but likely not ideal	Likely available	Not freely available		Not shortlisted
DNDC calculator	Available	Crops and livestock manure, direct GHG emissions	Simulation model for scientific use, not suitable for use by practitioners	Likely applicable but limited use	Available	Free software available		Not shortlisted
Agriculture and Land Use National Greenhouse Gas Inventory Software (ALU)	Likely available	Agricultural and forestry activities	Likely not, used for regional inventories	Likely not applicable	Likely available		Colorado State University	Not shortlisted

Tool	Criterion 1: availability of documentation	Criterion 2: targeted agro-ecosystem	Criterion 3: suitability for farm level assessment	Criterion 4: applicability to main farm types in Scotland	Criterion 5: availability of information on implementation	Comments on evaluation	Other comments	Suggestion
DairyGEM	Detailed documentation available	USA dairy	Suitable	Dairy farms only, likely applicable with modification	Not known		USDA	Not shortlisted
Integrated Farm System Model (IFSM)	Detailed documentation available	USA crops and livestock	Suitable	Likely limited applicabilty	Not known		USDA, very detailed biophysical model	Not shortlisted

Annex 2. Detailed comparison of the shortlisted tools

In this section, the tools potentially suitable for farm-level carbon audits are evaluated against the criteria set in the project plan. A detailed assessment is carried out for three tools (AgRE Calc, Cool Farm Tool, Solagro Carbon Calculator), while for the remaining shortlisted tools (GLEAM-i, Farm Carbon Calculator, CALM, EX-ACT, IMPACCT, CCAFS-MOT), a brief statement against each criterion is given and reasons why these are considered not suitable for audit purposes are explained.

Recommended tools

AgRE Calc

General purpose:
AgRE Calc is an agricultural resource efficiency calculator, developed by SRUC Research and staff from its consulting division (SAC Consulting). According to the developers, the tool determines on-farm emissions down to enterprise and per unit of output basis, which the developers state to be "the most meaningful comparisons when considering food production". The tool quantifies both direct and indirect on-farm greenhouse gas emissions and biomass (not soil) carbon sequestration. Unlike other tools compared here, this tool is certified to be PAS2050 compliant.

Transparency:
There are two alternative interfaces where the tool running; a user-friendly web version and an Excel version. The web version is the one that would potentially be used in carbon audits. That version tool is not transparent (source code not available) and detailed documentation does not exist. However, according to the developers, the functioning of the GHG calculations in the Excel version is identical to the web version. For this reason, the Excel version (and additional information provided by the developers) was used here to evaluate the scientific robustness and comprehensiveness of the tool. On this basis, the tool was considered to be fully transparent.

Comprehensiveness:
The emissions associated with crops include embedded emissions from fertiliser production and pesticides, CO2 emissions from application of urea and lime, Direct N2O emissions from synthetic and organic fertiliser use and crop residues, and indirect emissions from fertiliser application as a result of volatilisation, leaching and runoff. The emissions associated with livestock include emissions embedded in feed, CH4 emission from enteric fermentation and N2O and CH4 emissions from manure management. This tool does not take into account the herd-level impacts (embedded emission from brought-in animals) in livestock production, i.e. only the animals that are held on the farm in question are considered, not animals of the breeding herd (e.g. suckler cows in beef production, breeding birds in broiler production, sows

in pig meat production), unless these animals are kept on the same farm as the meat animals. This gate to gate approach is a common feature in all GHG tools considered here, except GLEAM-i. The emissions related to energy use are calculated based on the input data provided by the user on consumption of electricity, red diesel, white diesel, petrol, kerosene / burning oil, LPG, mains gas and coal. Biomass carbon sequestration based on the forested area within the farm is taken into account.

Range of applicability:
The tool covers all main agricultural production systems in Scotland. There are more than 40 crop and grassland systems, including the main cereals, oil crops, legumes, potatoes and other root vegetables, other vegetables, fruits and berries. All main livestock species are covered by the tool, including beef and dairy cattle, sheep, pigs and poultry (laying hens, broilers, turkeys, ducks). The livestock systems are classified further based on the enterprise type (e.g. Spring calving hill suckler cows, Spring calving upland suckler cows, Spring calving lowland suckler cows) and by a more detailed system description (e.g. Breeder/finisher, Breeder/store, Breeder/finisher plus purchases, Organic breeder/finisher). It should be noted that the main reason for the specification of the livestock enterprise types and systems by the user is benchmarking purposes, so the type of system itself does not always have effect on the calculations and outputs of the tool. Only in the beef and dairy systems, this will specify the default feed composition data. Similarly, also in the crop production, the selected system specifies only the crop-specific emissions associated to crop residues. Otherwise the emissions for each crop are only dependent on the input data given by the user (i.e. no crop-specific emission factors are used).

Scientific robustness:
The calculations are mainly based on scientifically approved IPCC Tier 2 methodology. The emission factors for embedded fertiliser emissions come from Carbon Trust Footprint Expert 3.1 and are specified only for the total N, P and K, not for different fertiliser types separately. IPCC emission factors are used for direct and indirect emissions from synthetic fertiliser use, organic fertilisers and crop residues, but again, these are not specified for different types of synthetic fertiliser, crop species, soil type, climatic conditions etc. Emission factors for electricity and fuels are taken from Defra/DECC's Greenhouse Gas Conversion Factors for Company Reporting. The embedded emissions from different livestock feed items (a total 64 items) are mainly taken from the FeedPrint[1] calculator. It should be noted that FeedPrint is a Dutch tool, and the emission factors in that tool are not country-specific. It should also be noted that the FeedPrint utilises a "Top-down" approach in calculating emissions from land use changes. This approach does not allow to specifically include emissions that are related to direct land use changes, e.g. in soya production. For this reason, using soya meal in livestock is likely to produce lower GHG

[1] http://webapplicaties.wur.nl/software/feedprintNL/index.asp

emissions in AgRE Calc compared to some other tools. For emissions from animal housing and manure management, IPCC Tier 2 emissions factors are used for different manure management systems (specified by the user). To calculate the enteric CH4 emissions and nitrogen excretion (which determines the manure N_2O emissions), an approach adopted from the FAO GLEAM model is used. In this method, the feed (and nitrogen) intake is calculated based on equations that utilise data on the type of the animal, body weight growth rate etc. This means that in the current version of the tool, the actual feed consumption data provided by the user is not utilised in calculating the manure emissions. This is a justified approach, especially in the case of grazing systems where the actual feed intake is impossible to measure in a practical way. Concerning the carbon sequestration, the user can specify the area and type of woodland within the farm. However, in the current version of the tool, the type or age of the forest has no effect on the calculations, but a constant biomass carbon sequestration rate is assumed for the whole forested area. Removal of biomass from the forest is not considered, and neither is soil carbon sequestration.

Practicality:
In crop production, the farm activities with potential GHG mitigation effect that can be assessed with the tool include reduction of fertiliser use and fuel use in field operations, and improvement in yield (affecting per-unit GHG emissions). The change between different crop production systems does not itself affect the calculated emissions in most cases, but the effects can occur through resulting changes in yield and fertiliser and fuel use. In livestock production, the embedded feed GHG emissions can be affected through changes in the feed composition (if known) and through the total feed consumption (affected e.g. by animal performance). In the current web version, the emissions from housing and manure management are not affected by the actual feed consumption data, as these emissions are calculated based on default feed intake equations. However, these emissions can be indirectly affected by improved animal performance, which will result in higher feed efficiency in the calculations. The actual feed composition (e.g. protein content) does not affect the manure emission in the web tool, as this is using a default nutrient composition in the calculations. The changes in the manure management system have direct effects on the emissions through system-specific emission factors. The carbon sequestration as calculated by the tool is affected by change in the forested area, but not by the type of forest in the current version.

The tool is currently freely available for farmers who need to register as a user. The web-based version is very easy to use. All data input cells that require compulsory information are clearly indicated. The output reports are easily accessible. The excel version of the tool is more complicated and suitable for expert use only.

Format of information provided:
Total farm GHG emissions and breakdown according to crop and livestock species and type of GHG (direct and indirect CO_2, N_2O, CH4) are given. These are expressed also per livestock unit or per hectare. Detailed results of the emission from separate sources within the farm are

available. Detailed and summary results for the whole farm and per enterprise can be compared to results from another scenario (or between three different years). Numeric data and informative charts are provided. The Excel version calculates also other sustainability indicators in addition to GHG emissions, namely eutrophication potential, acidification potential, primary energy use, abiotic resource use and economic values, but these are currently not available in the web version.

Legal aspects:
AgRE Calc is a commercial service owned and developed by SAC Commercial Ltd, the commercial holding company of SRUC. SRUC provides individual farmers in Scotland free access to the tool for auditing their own businesses but reserve the right to agree charges for other uses of the tool.

Repeatability:
The tool is specifically designed for repeated assessments. The results from up to three years can be shown simultaneously and comparisons can be made.

Overall statement:
This tool is technically very suitable for farm-level carbon audits.

Cool Farm Tool

General purpose:
The purpose of the tool is to "quantify on-farm greenhouse gas emissions and soil carbon sequestration". Furthermore, according to the developers, it can evaluate different management options, i.e. "stimulates thinking about management". The tool is a GHG calculator currently intended for product level calculations - outputting emissions for individual products produced on farm. Multiple products can be assessed on a single farm, but as separate "instances" of the tool. In this aspect, the tool differs from other tools considered here, since those tools handle the farm as a single unit and can combine the emissions associated with different products.

Transparency:
The current tool is web-based and not transparent (source code not available). However, full documentation of the tool is available. This includes Technical Documentation for the online Cool Farm Tool and a documentation of the dairy module of the tool (the principles of which are applied in other livestock modules). These documents and information provided by the representative of Cool Farm Alliance were used to evaluate the scientific robustness and comprehensiveness of the tool.

Comprehensiveness:

The emissions associated with crop production (CO_2, N_2O, CH_4) include emissions from fertiliser production (embedded), soil fertiliser induced emissions, soil CO_2 emissions (and carbon sequestration) resulting from management and land use changes (including addition of manure, crop reside, and straw to soil stocks), emissions from crop residue management, emissions from pesticide production and biomass changes from loss or gain of forest and changes in soil carbon stocks as a result of land use changes. Carbon sequestration is calculated based on changes in land use and land management during previous 20 years. The number of trees, their growth, planting and removal is also taken into account in carbon sequestration. The number of woodland types for which the tool has default values of carbon sequestration is currently quite limited. The emissions associated with livestock include emissions embedded in feed, emission from enteric fermentation and emissions from manure management, which are all summed to give the livestock total. Unlike any other tools compared here, the users of CFT can calculate their own carbon footprint for home-grown feed. Similarly as most of the tools assessed here (except GLEAM-i) this tool seems to apply gate to gate approach in livestock herd dynamics, i.e. it does not take into account the embedded emissions from brought-in animals, so only the animals that are held on the farm in question are considered, not animals of the breeding herd (unless these animals are grown on the same farm as the meat animals). The electricity and fuel use are based on user input data. Alternatively, in crop production the fuels use can be estimated by the tool based on default fuel consumption of field operations.

Range of applicability:
According to the Cool Farm Alliance, there are currently 6000 registered users. There were 10s of thousands of offline assessments from before the tool was online that are now being imported. The tool is applied in 95 countries. There are 53 members in the Cool Farm Alliance, including most of the world's largest multi-national food and beverage companies: Danone, McDonalds, PepsiCo, Kellogg, Unilever, Olam, McCain, Marks and Spencer, Tesco, Mars, Nestle etc. The tool is used by farmers, agronomists, crop advisors, corporates and development agencies.

The tool covers all main agricultural production systems in Scotland. There are more than 30 different crop species or crop categories the tool can handle. These include the main cereals grown in Scotland, potatoes, beans, berries etc. (rapeseed is not included in the list of default crops). Default values for soil conditions are given by the tool (these can be modified by the user). The livestock species included in this tool are beef cattle, dairy cattle, sheep, pigs, chicken, turkeys and ducks (and also buffalo, goats, camels, horses and rabbits). For dairy cows, it is possible to select from 14 different breeds, and the tool selects breed-specific default values for the livestock physical properties (these can be changed by the user). The user can specify the number of animals in different categories such as milk cows, dairy calves, meat calves, heifers, dry cows, and nursing cows. For beef cattle, the user can select either breeding farm or intermediate/finishing farm (but not the both systems at the same time). For each farm, the user can select either organic or conventional production and the number of animals and their starting/finishing weight in different categories. For other livestock, the information given by the user is much more limited. The user can only select the livestock species, and the number animals in different phases (“juvenile”, “adult productive”, “adult non-productive”) and the length of each phase.

In general, it should be noted that with CFT, it is only possible to assess one production system each time, not the whole farm, even if there would be several production systems at the same farm.

Scientific robustness:
Of all tools considered here, Cool Farm Tool applies the most detailed method for calculation of soil GHG emissions, and goes beyond the IPCC Tier 1 and Tier 2 methods. Emissions of N_2O from the processes of nitrification and denitrification (direct emissions) are modelled in the CFT using an equation by Bouwman et al. 2002. This equation has different emission factors for different types of fertilisers and different soil conditions. Volatilisation to NH_3 (indirect N_2O emissions uses the equation from FAO and IFA, applying emission factors associated with particular properties of the relevant growing area and fertiliser application. The default factors from IPCC are used to estimate the amount of N lost through leaching and resulting as N_2O. The formulae to calculate emissions from $CaCO_3$ and urea are standard factor multiplications (IPCC EFs). In general, the factors affecting soil emission include the following: 1) Application rate, 2) Fertiliser type, 3) Crop type, 4) Soil texture, 5) SOC, 6) CEC, 7) Soil pH, 8) Drainage, and 9) Application method. Embedded emissions from mineral fertilisers are based on LCA principles, i.e. they include “all relevant activities and emissions from raw material supply up to the final product at factory gate”. Emissions related to fertiliser production are country-specific. Changes in soil organic carbon are modelled for a 20 year period and are affected by soil type, management (tillage) and C input to soil. The impact of addition of manure, crop residue, and straw on soil stocks is modelled using multipliers from Smith et al. (2008).

All livestock modules make use of Tier 2 approach for manure management, i.e. specific N excretion factors and volatile solids amounts are calculated in the tool based on the feed intake. However, for other livestock categories except cattle, the emission calculations use a very simplistic approach, which allows very little input from the user and is mostly based on default values of animal performance (which are not transparent). The feed intake is always an input that can be given by the user (also the grazing percentage, grazing type and quality should be given). In the case of grazing, the tool calculates the dry matter intake based on the grazing time, but also this value can be overwritten by the user. In the case of dairy cattle, there is an option to allow the tool to estimate the feed intake based on the energy requirements calculated on the basis of milk production data and energy calculation formulas from the IPCC (2006) guideline. Also this value can be overwritten by the user. For each feed item included in the animal diet, the user should specify the average daily dry matter intake in each animal category. The feed composition can be specified using 29 feed items, mainly based on FeedPrint (Dutch) data. These data are used to determine the feed embedded CO2, dry matter, gross energy, digestible energy, crude protein and phosphorus (P) content. It seems that direct effects of land use changes are included in the emissions associated with certain feed ingredients (e.g. soya). Alternatively, the users can calculate their own embedded GHG emissions for home-grown feed ingredients.

Practicality:
The farm activities with potential GHG mitigation effect that can be assessed with the tool include in crop production the reduction of total fertiliser use, the change between different types of fertilisers, fuel use in field operations, and improvement in yield (affecting per-unit GHG emissions). The change between different crop production systems has also a direct effect on the calculation of emissions and it has also effect through resulting changes in yield and fertiliser and fuel use. In livestock production, the embedded feed GHG emissions can be affected through changes in the feed composition and through the total feed consumption (which is an input given by the user).The emissions from housing and manure management are directly affected by the actual feed consumption data, according to IPCC Tier 2 calculations. With the exception of cattle production, changes in animal performance (through other mechanism than feed intake) have very little effect on the emissions, since the performance is not part of the inputs given by the user. The changes in the manure management system have direct effects on the emissions through system-specific emission factors. The carbon sequestration as calculated by the tool is affected by changes in the land use, land management, and the growth/planting/removal of trees. However, the number of woodland types the tool can handle in currently quite limited.

The tool is currently freely available for farmers who register as a user. The web-based tool is very easy to use, and requires relatively small amount of input data. Good instructions for data input are provided in separate documents, and the interface also provides instructions. Some data entries may by slightly confusing as the units are not always clearly explained (e.g. does “kg” mean kg/day or kg/year?).

Format of information provided:
Total GHG emissions of the production system and breakdown according to the source of the emission and the type of GHG (CO_2, N_2O, CH_4) are given. These are expressed also per tonne of product and per hectare. Total emissions and their breakdown can be directly compared to results from another production system or to another selected year. Numeric data and informative charts are provided. The tool can also calculate income, expenditure and profit (total, per hectare and per unit of product), based on unit values provided by the user.

Legal aspects:
The Cool Farm Tool is owned by the Cool Farm Alliance Community Interest Company, a not for profit membership organisation, with members drawn from the private sector, NGO's and research organisations. The tool was originally established as a collaborative project between The University of Aberdeen, The Sustainable Food Lab and Unilever. Over the years the Cool Farm Tool has received many public funding grants such as from the research councils, mostly

in partnership with academic members. For farmers, there is free access to tool after registration but this allows only limited number of assessments. Modification to the licence can be negotiated with Cool Farm Alliance, to ensure the practical use for different purposes.

Repeatability:
The tool can simultaneously show comparison between two different years which can be selected by the user.

Overall statement:
This tool is technically very suitable for farm-level carbon audits.

Solagro (JRC) Carbon Calculator

General purpose:
This tool was developed (and is handled) by Solagro, France, for the European Commission Joint Research Centre (JRC). It is described as "a comprehensive tool assessing and promoting the efforts of European farmers to produce according to carbon-neutral or low emission farming practices". The aim of development was the create a farm-level carbon calculator that 1) is suitable for the main farming types in the whole EU, 2) presents the carbon footprint results both at the farm and product scale, and 3) generates farm-specific mitigation action recommendations (Tuomisto et al. 2015). According to the developers, "the Carbon Calculator can be used by a wide range of people, (e.g. farmers, agricultural advisors and trainers). The Carbon Calculator is a tool to assess greenhouse gas (GHG) emissions from farming practices and mitigation potential at farm scale. The objective of the assessment is also to compare farm practices between other farms with similar productions".

Transparency:
The tool is running in Microsoft Excel, and Visual Basic for Applications (VBA) is used for creating user forms for data entry. Calculations are partly transparent, as much of the built-in data can be made visible in Excel. However, the VBA code is not visible to the user. A detailed technical description of the tool is provided, together with sources of the secondary data, emission factors etc. This documentation was used (together with the data visible in the Excel sheet, and communication with one of the original developers of the tool) to assess the scientific robustness and comprehensiveness of the tool.

Comprehensiveness:
This tool can be considered to be the most comprehensive of all tools evaluated here. According to the developers, "a life cycle approach has been favoured for the design of this tool, i.e. considering all emissions from upstream of the farm (cradle) to the farm gate". The calculated emissions include N_2O emissions for the following sources: direct emissions from chemical nitrogen fertilizer applications, manure applications to agricultural soils, crop residues (i.e. leguminous) and grazing / pasture. Indirect N_2O emissions include the following: NH3

depositions on soils and leaching / run-off of nitrates to water. The (embedded) N_2O emissions form processing of inputs include chemical and mineral fertilizers, feedstuffs for animals and buildings and machinery. CH_4 emissions include enteric fermentation, manure management (housing and storage) and crop residues burnt. CO_2 emissions include direct farm emissions (diesel fuels, other fuels) and indirect energy emissions (electricity) and other indirect emissions (inputs processing: fertilisers, feedstuffs, machinery). Renewable energy is also taken into account (offset of emissions). CO_2 emissions (or carbon sequestration) includes also changes in carbon stocks, driven by practice changes and land use changes (e.g. crops <-> grasslands) and trees, hedges permanent crops and agroforestry on the farms. Unlike other tools, this tool also takes into account HFC, PFC and SF6 emissions form cooling storage, machinery, cooling buildings and transport. Despite being based on the LCA approach, the tool does not seem to take into account the herd-level impacts in livestock production, i.e. only the animals that are held on the farm in question are considered, not animals of the breeding herd, unless these animals are grown on the same farm as the meat animals. This (gate to gate approach) is a common feature in all GHG tools considered here, except GLEAM-i.

Range of applicability:
The tool has been developed to be used within the EU-27 area, and it has country specific built-in data for most European countries, including UK. According to the developers, the tool is suitable for all farm sizes and farming systems (i.e., organic, conventional, integrated, and conservation farming).The tool was tested using survey data from 54 farms from 8 EU Member States, one third of them being from the UK (Tuomisto et al. 2015). The tool delivers its results both at the farm level and as allocated to up to 5 main products of the farm.

All main European crop species are covered by the tool, including the main crops grown in Scotland (for example barley, wheat, peas, oat, rape, spring field bean, winter field bean, various forage species, potato, strawberry, turnip, green pea, green bean, carrot etc.). The livestock species handled by the tool are dairy cattle (different animal categories), beef cattle (different animal categories), goat (milk and meat), dairy and meat sheep (different animal categories), horses, donkeys, pigs (different animal categories, sow and meat animal systems), broilers and laying hens (different production systems), rabbits, geese and game birds.

Scientific robustness:
Of all tools compared here, this tool follows probably most closely the international standards for Life Cycle Assessment and aims to include all important direct and embedded GHG emissions in the calculations.

For emissions from crop production, this tool applies a relatively simple approach for soil N_2O emissions, based on the IPCC (2006) Guidelines for National Greenhouse Gas Inventories. The direct emissions are dependent on the type of fertiliser used, and the emission factors are taken either from Bouwman et al. (2002) or from the IPCC (2006) guidelines (Table 11.1). The calculation of direct N_2O emissions from grazing animals is determined by the amount of N deposited on pasture by grazing animals through urine and dung, and the calculations are based on 2006 IPCC Guidelines. Direct N_2O emissions from organic fertilisers depend on the amount of animal manure, sewage sludge, compost, other organic amendments (rendering waste, guano, brewery waste) applied to soils. Direct emissions from crop residues are crop-specific and calculated using IPCC emission factors. CH_4 and N_2O emissions from burning of the residues are also taken into account. Emissions from drained and managed organic soils are included in the calculations. The calculations of indirect N_2O emissions from leaching differ from the 2006 IPCC Guidelines and other tools compared here. The nitrogen amount potentially submitted to leaching and runoff is calculated based on nitrogen balance at the farm level, i.e. differences between N input and N output estimations. The leaching rate is based on soil properties and climate. Indirect N_2O emissions following N volatilisation depend on the fertiliser type, soil pH (can be approximated regionally) and climatic conditions. The emissions form liming and urea fertilization are not taken into account since it is stated that “the GHG balance from the industrial process to farming applications is null”.

In the livestock module, the assessment of GHG emissions from enteric fermentation is based on the 2006 IPCC Tier 2 simplified method for all livestock categories. Dry matter intake is calculated based on energy requirement (IPCC Tier 2) in ruminants. In pigs and poultry, this is based on feed consumption data. If that data are not given, default values for each animal type are used. Methane emissions from manure management are calculated based on volatile solid excretion (based on dry matter intake), type on animal and the manure management system. Direct N_2O emissions from the treatment and the storage of manure are estimated with the IPCC Tier 2 method, and depend on nitrogen excretion per head and by animal category, proportion of manure management system for each category, and emission factor for each manure management system.   It should be noted that the amount of nitrogen excreted by the animals is based on IPCC Tier 1 emission factors (i.e. it is constant amount specific for each animal category and not affected by feed intake or feed composition), unlike in the case of other tools evaluated here. The developers state that the 2006 IPCC (Tier 2) methodology, taking into account N intake in the diet and daily N retained per animal of category has not been used because the percentage of crude protein in diet and the net energy for growth are not easily available. Embedded emissions from fertilisers, animal feed, buildings, machinery etc. are included. Constant emission factors are used, including the emission factors for feedstuff (based on GESTIM, 2011). The tools have default emission data for 17 single feed ingredients (which is considerably fewer than in some other tools in this comparison), and 35 categories of compound feed (a limited number of these is available for each species). It seems that direct land use change emission (e.g. from soya production) are not taken into account. The electricity emission factors are country-specific. The end-of-life of organic matter outputs of the farm and of plastics used on the farm are taken into account in the assessment.

Of all tools compared here, this tool uses by far the most detailed method to calculate soil carbon stock changes (carbon losses or carbon sequestration). These changes are affected by changes in land use and management, and are calculated based on IPCC land use and land management factors (e.g. full tillage, reduced tillage, no tillage), specific for land use, soil type, management type, and climatic conditions. Soil carbon stocks can be increased through return of crop residues, using organic amendments and green covers. Carbon storage in natural elements (such as trees, hedges, shrubs and heath) is taken into account. Carbon sequestration through tree growth is based on default values which can be customised by the user if national data are available.

Practicality:
The tool is currently freely available for registered users. The tool has been developed in Microsoft Excel, and Visual Basic for Applications (VBA) is used for creating user forms for data entry. Therefore, according to the developers, specific skills for using Microsoft Excel spreadsheets are not required. The interface is mainly clear and easy to use, but when testing the tool, entering the data resulted in numerous error messages, and handling them was time consuming. The developers also state in accompanying documentation that "It is not always easy for the user to identify by himself which data are necessary. For that reason, a training session is often necessary for users to better understand: data needs, how to collect them with a farmer, where to put them in the tool, and GHG and energy results provided at the end of the assessment."

The farm activities with potential GHG mitigation effect that can be assessed with the tool include in crop production the reduction of total fertiliser use, the change between different types of fertilisers, fuel use in field operations, and improvement of yield. In livestock production, the embedded feed GHG emissions can be affected through changes in the feed composition and through the total feed consumption. However, it is not possible to assess the reduction of the manure emissions resulting from changing feeding, because of the Tier 1 method used for these emissions. The changes in the manure management system have direct effects on the emissions through system-specific emission factors. The carbon sequestration as calculated by the tool is affected by various changes in the land use, land management, and the growth/planting/removal of trees.

In the Results section, the tool shows up to 16 mitigation or sequestration actions that are used to quantify potential mitigations of GHG emissions. These actions are the following:
1) Adjust N fertiliser balance, 2) Soils covered all the year, 3) Introduction of legumes in the rotation, 4) Introduction of legumes in grasslands, 5) No-tillage, 6) Agroforestry, 7) Avoid burning residues, 8) Reduce methane from enteric fermentation, 9) Change in slurry management system: cover/crust, 10) Biogas production, 11) Reduction of electricity consumption of the milking system, 12) Reduce engines fuel consumption (test and eco driving), 13) Solar panel on suitable buildings, 14) Heat water with solar panel, 15) Wood boiler, and 16) Implementation of hedges and other landscape elements.

Format of information provided:

The results are presented in form of relatively clear tables (and with some graphics). The summary results include total GHG emissions at farm level, expressed in tCO_2e/ha and the main sources of emissions at farm level, total GHG emissions for one to five main products of the farm with tables showing the sources of emissions per product, expressed in tCO2e/unit, and the top five GHG sources at product level. The summary results also include the total GHG emissions at farm level for the main gases: CO_2, CH_4, N_2O, HFC and CO_2 from C stock changes, and also the GHG emissions potentially avoided as a result mitigation and sequestration. In addition to the GHG emissions, the summary results also present other environmental indicators, namely 1) Water consumption, 2) Direct primary energy consumption, 3) Nitrogen surplus and 4) Ammonia volatilization.

The presentation of results for detailed GHG emissions (by sources and gases) is based on the European Commission Organisation Environmental Footprint (OEF) guide and show 1) GHG emissions from direct activities (non-mechanical sources, enteric fermentation, manure management, direct and indirect emissions from soils, and burnt crop residues), and 2) GHG emissions from indirect activities: consumption of purchased electricity and other indirect energy sources like collective irrigation or water pumping, fuel from thirds (contractors, etc.), all other indirect sources from manufacturing and transportation (e.g. agrichemical production and product processing).

The results also show detailed distribution of the emissions between separate products produced at the farm, and the allocation of the emission between products originating from a single system (e.g. milk and beef from dairy cattle, eggs and meat from hens).

Legal aspects:
The Carbon Calculator was financed by EU and is freely available. It was first a demand from the COMAGRI (European Parliament) to get a carbon tool at farm level. Then, the DG Environment asked the JRC to launch a public call of tender and Solagro was selected to develop the tool. The tool is currently managed by Solagro.

Repeatability:
The calculations are technically repeatable, but there is no option to show results from different years simultaneously. Instead, it is possible to compare the emissions from the farm in question to the average, maximum and minimum values from other farm. The data from other farms need to be entered manually (if known).

Overall statement:
This tool is technically very suitable for farm-level carbon audits.

Other shortlisted tools

GLEAM-i

General purpose:
The purpose of the tool is to calculate the greenhouse gas emissions of livestock, "but also can be used as a scenario assessment tool for different adaptation and mitigation options". According to FAO, “GLEAM-i is the first open, user-friendly and livestock specific tool designed to support governments, project planners, producers, industry and civil society organizations to calculate emissions using Tier 2 methods. GLEAM-i can be used in the preparation of national inventories and in ex-ante project evaluation for the assessment of intervention scenarios in animal husbandry, feed and manure management.”

Transparency:
The tool is running in Excel but the background data used in the calculations is not visible. Full documentation of the technical details is available.

Scientific robustness:
The tool applies the LCA framework is defined in ISO standards 14040 and 14044 (ISO, 2006a and ISO, 2006b). Calculated feed intake is based on estimated energy requirement of animals (i.e. actual feed consumption cannot be given by the user). This is calculated based on equations from scientific literature, and the sources given in accompanying documentation. It should be noted that recent studies have found some of these equations to be out-of-date, and therefore they may not predict the actual feed intake very accurately (e.g. Leinonen et al. 2018). For emissions from housing and manure management, the IPCC Tier 2 method is mainly used. Embedded emissions for feedstuffs are built in the tool and are based on various sources, including the LEAP (2015) database. The user can select form various feedstuffs in all animal categories and specify their proportions in the rations.

Comprehensiveness:
The tool can be used for livestock systems only. The tool is based on calculated herd size, depending on the entered numbers of reproductive females. Therefore, the outputs always cover the whole herd (for example for beef cattle suckler cows, heifers, adult males, juvenile males and meat animals), regardless if all these animals are grown on the farm in question or not. Because this tool works at the herd level, it is the only tool that takes into account the whole livestock production chain in the calculation of the emissions.

The tool takes into account all N_2O, and CH_4 emissions arising from livestock housing, grazing and manure management, and the embedded GHG emissions from feed production, processing and transport.

Although the direct farm energy consumption is included in the results, the Excel tool has no option to have it as an input the user could enter. Therefore, it seems to be based on some default baseline values.

Range of applicability:
The GLEAM tool is widely used for assessing GHG emissions from livestock by FAO and other users from different countries. The tool covers all main Scottish livestock species: beef cattle, dairy cattle, sheep, pigs, laying hens, broilers (other species included in the tool are buffalo and goats). Different production systems modelled as follows. Cattle: grassland based or mixed, Sheep: dairy and non-dairy, both grassland based or mixed, Pigs: backyard, intermediate or industrial, Chicken: backyard, layers or broilers. The Excel version of the tool does not include separate free range or organic systems for pigs or chicken.

Practicality:
The tool shows relatively clear input sheets and results. If the user does not change any specific input, a default value is shown and used in the calculations. Entering the inputs is rather complicated, however, especially because the tool is not designed for farm level use. The default number of animals for all animal categories is given, and the user should go through all input sheets to change this number, even if there are no animals in a specific category (in that case the number should be set to zero). More importantly, the user should always enter the number of reproductive females in the herd (and the number of animals in all categories is calculated based on this). This number is often impossible to be known by the user, especially when there are no reproductive animals on the farm (for example, if there are only finisher cattle, lambs or pigs, laying hens or broilers). Furthermore, the user can not specify the quantities of any farm-level inputs (other than the animals) including feed and energy consumption.

Format of information provided:
Results are given both in numeric format and informative graphs. Results can be exported to separate output excel files. The tool gives total GHG emissions (at the herd level) and detailed breakdown by animal species, source and form (CO_2, N_2O, CH4). Also emission intensities are shown, i.e. amount of emissions per unit of protein. Note: it is not possible to have breakdown by animal cohort, e.g. cows, sows, meat animals.

Legal aspects:
The tool is freely available. No registration is needed.

Repeatability:
The tool shows simultaneously two sets of results, “baseline” and “scenario”. These can represent for example two separate years.

Overall statement:

This tool is not suitable for farm level carbon audits. The tool is not designed for farm level use and entering the actual farm data would be very complicated. The comprehensiveness of the tool is limited (energy use not included in inputs), and the format of the results is not very informative.

Farm Carbon Calculator

General purpose:
The tool is part of Farm Carbon Cutting Toolkit, an organization which is a “vehicle for farmers to connect with other farmers to reduce their greenhouse gas (GHG) emissions”. According to their website the Farm Carbon Calculator is "a free tool for farmers and growers to work out the greenhouse gas emissions and carbon sequestration associated with their business"

Transparency:
The tool is not transparent but some sources of secondary data given in a separate excel file.

Comprehensiveness:
The tool calculates emissions from fuels, embedded emission from some materials and capital items, emissions from crop production (field emissions and embedded emission from fertilisers sprays) and livestock, embedded feed emissions, emissions from waste management, carbon sequestration based on the area of woodland and other natural elements. Different manure management systems are taken into consideration. The tool includes a very limited list of different feedstuffs. In general, the inputs for livestock are rather limited.

Range of applicability:
The tool is applicable for selected arable crops: wheat, oat barley, maize, OSR, sugar beet, rye, triticale, beans, peas, lupins, soya, and for livestock: beef and dairy cows, pigs, sows, sheep, goat, horses, dear, broilers, breeding chicken, layers, pullets, turkey, ducks. Options for carbon sequestration are included.

Scientific robustness:
This cannot be evaluated based on the lack of documentation. The overall approach to GHG emission is not clearly stated and the details of the calculations are not known. For example it is not clear how the emissions for field operation, livestock housing and manure management are calculated. Therefore, the validity of the results and outcomes of mitigation measures is questionable. Test runs of the tool produced some unexpected output values.

Practicality:
Very easy to use, but due to lack of documentation it is very difficult figure out which mitigation methods can be actually handled by the tool.

Format of information provided:

The outputs are presented in tables and some graphics are also used. Total CO_2e emissions, their breakdown and percentages of total are given.

Legal aspects:
The tool is freely available after registration. There are no known restrictions of use.

Repeatability:
Assessments can be repeated but there are no options for direct comparison e.g. between years.

Overall statement:
Although designed for farm level use, this tool cannot be considered as a suitable option for farm-level carbon audits. The scientific robustness of the tool and the validity of the results cannot be evaluated due to lack of documentation. The inputs that can be given by the user are rather limited especially in the case of livestock. This makes it difficult to assess any mitigation methods.

CALM

CLA, the owner of this tool stated that they do not recommend it to any new users, as it has not been updated, and they only keep it going to provide consistency for those who still use it. For this reason, the tool could not be evaluated here and it is also not an option to be used for carbon audit purposes.

Overall statement:
This tool is not available for farm-level carbon audits. Evaluation against the criteria could not be carried out.

EX-ACT

General purpose:
The Ex-Ante Carbon-balance Tool (EX-ACT) is an appraisal system developed by FAO providing estimates of the impact of agriculture and forestry development projects, programmes and policies on the carbon balance. Such projects include large scale (landscape level) land use changes, deforestation, reforestation, changes in production systems etc. Although it has been widely used for this purpose (numerous papers and reports have been published) it cannot be considered to be an ideal tool for quantifying farm level GHG emissions.

Transparency:
The tool is not transparent. Technical documentation is freely available.

Scientific robustness:

The calculations are based on IPCC guidelines. Due to complexity and different intended use compared to the tools specifically developed for farm-level assessment, the technical details of the tool were not fully evaluated here.

Comprehensiveness:
The tool can handle large-scale system changes and resulting emissions from carbon stock changes per unit of land, and CH_4 and N_2O emissions. In contrast, it cannot take into account small scale changes in farm management.

Range of applicability:
The systems covered by the tool include the following. Forestry; Crop in different categories: grains, root crops, tubers, wheat, barley, maize, oats, potatoes and soybeans; Livestock in different categories: dairy cattle, other cattle, buffalo, sheep, swine (market), and swine (breeding).

Practicality:
The tool is rather complicated to use. Detailed (Tier 2) calculations applied in the tool require a lot technical data. The tool cannot directly utilize farm-level input/output data.

Format of information provided:
The tool provides detailed tables and figures on high-level changes in GHG emissions (i.e. not farm level).

Legal aspects:
The tool is freely available.

Repeatability:
Technically the calculations are repeatable.

Overall statement:
The tool is not designed for farm-level assessment or handling farm data and therefore it is not suitable for farm-level carbon audits.

IMPACCT

General purpose:
According to the University of Hertfordshire website, “IMPACCT was a European Commission research project that developed a software tool to help European agriculture reduce its climate change impacts. The tool was designed to help farmers and growers to take action so as to reduce their greenhouse gas emissions and improve carbon sequestration by modifying farming practices. It also supports policy makers in the development and improvement of climate change mitigation policies”.

Transparency:
The tool is not transparent, sources of secondary data not known. There is no technical documentation available.

Scientific robustness:
Scientific robustness cannot be evaluated due to the lack of documentation. The overall approach to GHG emission is not clearly stated and the details of the calculations are not known. For example it is not clear how the emissions for field operation, and livestock housing and manure management are calculated. The tool can handle mainly qualitative input and therefore it seems clear that it is largely based on built-in default data that cannot be changed by the user.

Comprehensiveness:
It is not clear which GHG emissions and which sources are included in the calculations. Most important farms activities are included in the data input sheets as on/off options; some of these show obvious mitigation opportunities but some look quite trivial. There is a very limited amount of quantitative input data that can be entered.

Range of applicability:
The tool is applicable for a limited number of production systems: beef, dairy, pigs, sheep, cereals, oilseed, protein crops, vegetables, fruits.

The University of Hertfordshire website lists 23 European case studies on agricultural GHG mitigation originating from the IMPACCT project. Three of these are from Scotland, However, it is not made clear how the tool was utilised in those projects, and very little quantitative information is provided.

Practicality:
The tool is easy to use and it is very fast to enter the required inputs, as most of these are just qualitative yes/no options. The tool lists numerous mitigation options and gives quantitative estimates of the baseline of the emissions and the mitigation potential. Note: the baseline seems to be very much based on some defaults data that is not visible to the user.

Format of information provided:
Detailed results on different GHG mitigation methods are available, but it is very difficult understand the processes behind the results and it is difficult to put them into the context. Some visualisation is available. Also qualitative economic information is provided for different mitigation methods.

Legal aspects:
The tool is freely available.

Repeatability:
Technically the calculations are repeatable.

Overall statement:
The tool is not suitable for farm-level carbon audits. The scientific robustness of the tool and the validity of the results cannot be evaluated due to lack of documentation and transparency. The quantitative inputs that can be given by the user are rather limited. This makes it difficult to assess the mitigation methods provided by the tool.

CCAFS-MOT

General purpose:
The Climate Change, Agriculture and Food Security Mitigation Options Tool (CCAFS-MOT) was developed at the University of Aberdeen, in partnership with CCAFS, the International Centre for Tropical Agriculture, and the Gund Institute for Ecological Economics at the University of Vermont, and with support from the United States Agency for International Development. CCAFS-MOT is an Excel tool to support policy advisors and agricultural extension services on the choice of management practices that reduce greenhouse gas emissions (GHG) without risking crop yields. The tool is designed for crop production and it is not designed for use at a farm level.

Transparency:
The tool is not transparent. No detailed technical documentation could be found, but the general functioning of the tool is described in a scientific paper (Feliciano et al. 2017).

Comprehensiveness:
The tool calculates the direct and indirect GHG emissions from agricultural soils and livestock. It does not include emissions from machinery or other primary energy (fuel) use. Greenhouse gas emissions from the production of synthetic fertiliser are considered. Although the livestock emissions cover all main sources and GHGs, the calculations of those are largely based on default values, and cannot be affected by the user by entering actual farm data.

Range of applicability:
The tool is intended to be used in any region of the World (the user should specify the country in question). Numerous crop species and species groups are covered, including the crops grown in Scotland. The livestock species included are dairy and beef cattle, small ruminants, pigs and poultry. There are not very detailed specifications for livestock production systems.

Scientific robustness:
The direct (N_2O), and indirect (NO and NH_3) emissions from fertiliser use are calculated as a combination of mechanistic models (e.g. Bouwman et al. 2002) and IPCC emission factors. Losses of soil carbon as a result of land use changes are based on IPCC emissions factors.

Emissions from burning cropland residues are also taken into account. The livestock emissions are calculated in a very simple way. The tool uses only the livestock type, number of animals as an input and combines these with a region-specific emission factors. All other livestock information (including feed consumption and feed composition) are based on default values.

Practicality:
The tool is very simple to use as it requires only minimal amount of inputs. Various mitigation methods and their potential effect on GHG emission can be immediately seen in the results. The crop section of the tool is very informative, as the effect of changes in the input can be directly explored. This is not possible for the livestock section, which is based on default values.

Format of information provided:
The tool produces relatively simple outputs showing total GHG emission (also per ha, per head, or per selected product). The breakdown of the emissions originating from different sources is shown. Quantitative mitigation potential is also presented.

Legal aspects:
The tool is freely available.

Repeatability:
The calculations are technically repeatable.

Overall statement:
Although the tool is very informative when assessing GHG emissions from crop production, it is not comprehensive enough (i.e. does not include all significant sources of emissions) to be used for farm-level carbon audits. For livestock production, it is not possible to consider small scale management practices, and therefore the tool is not suitable for farm level assessment of GHG emissions.

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Annex 3. SWOT and PESTLE analysis

Methodology

SWOT analysis is a commonly used tool for decision making in relation to a strategy, project or product in its environment. It is a simple, but systematic approach to “kick start” the strategy planning process, whereby internal and external factors considered important for the future of the project/product/strategy are categorised as favourable or unfavourable, yielding four categories (SWOT groups): strengths, weaknesses, opportunities and threats (Figure 1). The purpose of applying SWOT to a strategic planning process is usually to develop and adopt a strategy resulting in a good fit between the internal and external factors (Nixon and Helms 2010).

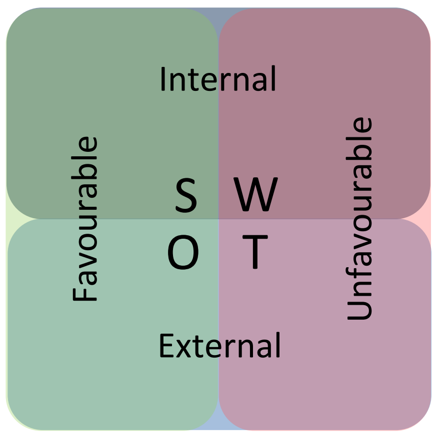

Figure 1 SWOT factors

The SWOT analysis was here applied in relation to the question: *What are the important factors in promoting an on-farm greenhouse gas calculator in Scotland at a national level?* In addition, what are the specific factors related to individual tools? (The counterfactual being the expected uptake of a wide range of GHG calculators promoted by diverse actors in the industry in the coming decade.)
To the request of CXC, the SWOT analysis was considered in a PESTLE framework, which explicitly considers factors in six areas: political, economic, social, technological, legal and environmental areas.

Findings

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Strengths

Comparability across a large number of Scottish farms
Enabling crude upscaling to national level (if central dataset is used)
Efforts and investment can be co-ordinated
Industry-wide credibility
The tools generally present both emission intensity (emission per amount of produce) and total emissions
The shortlisted tools require only basic computer technology on farm

Tool specific strengths:

CFT would potentially allow international comparison, the Solagro Calculator potentially would allow European comparison
Solagro Carbon Calculator suggests farm-specific mitigation options
AgRE Calc has a financial module (in the Excel version only), CFT applies simple economic calculations

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Weaknesses

Each tool can only account for certain GHG reductions on farms; a range of mitigation actions are not built in
Maintenance and development requires continuing public investment (e.g. continued harmonisation with the national GHG inventory, implementation of novel mitigation options, building in new evidence, links to new datasets, responding to users' needs, data extraction and analysis)
The tools do not consider other environmental aspects in detail, therefore key trade-offs might be overlooked in the decisions

Tool specific weaknesses:

Soil C sequestration is not represented in AgRE Calc
The three recommended tools do not consider embedded emissions in livestock bought in
CFT provides only product-specific results, not combined results for the farm

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Opportunities

Many industry actors are ready to use such tools
The tool could be developed so that it is to some extent harmonised with national GHG inventory
The use of the tool can provide Scotland-specific data for the national GHG inventory calculations
Emerging digitalisation and big data could provide information sources for the tools
A harmonised approach could yield international credibility

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Threats

The implicit environmental political assumptions in the tool on international effort sharing and land use used (via LCA parameters) become guiding on-farm decisions in Scotland – i.e. these need to be aligned to wider land use policy goals
Sole focus on the tool's recommendation can divert focus from possible solutions not represented in the tool
Imperfections in the chosen tool's methodology might solidify
The complexity of data ownership and privacy might impede the use of the data beyond the individual farmer

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	- Industry-wide agreement is preferable to be able to build the credibility of the tool, particularly as various tools are available, all giving different results - If different tools will be taken up in the Devolved Administrations then retailers looking for standard approaches might show a preference to the bigger supplier market

8. References

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