A comparison of carbon accounting tools for arable crops in the United Kingdom

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1. Abstract

In light of concerns over climate change and the need for national inventories for greenhouse gas reporting, there has been a recent increase in interest in the 'carbon foot printing' of products. A number of LCA-based carbon reporting tools have been developed in both the agricultural and renewable energy sectors, both of which follow calculation methodologies to account for GHG emissions from arable cropping. A review was performed to compare 11 existing greenhouse gas (GHG) accounting tools produced in order to calculate emissions from arable crops, either for food or bioenergy production in the UK, and a multi-criteria-analysis was performed to test their relative strengths and weaknesses. Tools designed for farm-based accounting achieved a higher 'user-friendliness' score, however bioenergy-based tools performed better in the overall level of information provided in the results, transparency and the comprehensiveness of emission sources included in the calculations. A model dataset for UK feed wheat was used to test the GHG emissions calculated by each tool. The results showed large differences, mainly due to how greenhouse gas emissions from fertiliser manufacture and application are accounted for. Overall, the Cool Farm Tool (Hillier et al. 2011) was identified as the highest ranking tool that is currently available in the public domain. The differences in the results between the tools appear to be due to the goal and scope, the system boundaries and underlying emission factor data.

Keywords: Carbon accounting; agriculture; Life cycle analysis; Greenhouse gas reporting

2. Introduction

2.1. Climate change and everyday products

Concern over world-wide climate change has led to an increased interest in identifying major sources and sinks of carbon and greenhouse gases (GHG). The UK is committed to providing annual GHG reports to the UNFCCC and European Union as part of its legally binding Climate Change Act, committing it to reduce total National GHG emissions by 80% by 2050, using 1990 emissions as a baseline (HM Government 2007). National-level reporting involves assessing sources and sinks of emissions from various sectors including the energy, transportation, agriculture, forestry sectors and identifying land use changes that have occurred over time. Methodologies for GHG accounting on a National level have been developed through a widespread scientific panel of experts in the UNFCC and IPCC, and in parallel to this, there has also been a number of GHG tools developed to assess agricultural and forestry practices (Colomb et al. 2012) and changes in soil carbon due to land use change (Coleman & Jenkinson 2008; Miao et al. 2011; Palosuo et al. 2012).

The Climate Change Act has 'galvanised' interest in sustainability issues over all sectors of the economy (Gadema & Oglethorpe 2011). In 2008, the Department for Transport introduced the Renewable Transport Fuel Obligation (RTFO), which posed a "legal obligation on fossil fuel producers to produce or supply renewable transport fuel" and defines the GHG calculation methodology that biofuel producers must use to report their GHG emissions (RFA 2010). Since then the European Commission's Renewable Energy Directive (RED, EC 2009), has been developed by the European Parliament and the Council of the European Union as part of the Climate Change Package agreed in December 2008. The RED was established to promote the uptake of energy from renewable resources, and it provides targets for participating Member States to commit to (Whittaker et al. 2011). The RED introduces sustainability criteria that specify that areas of high carbon and biodiversity must be preserved and requires that any changes in land use due to biofuel production are accounted for. The RED states that the GHG savings from biofuels should be at least 35% before January 2017, 50% after, and 60% after January 2018 for installations that start on or after 1 January 2017. The RED specifies a GHG reporting methodology by which calculations must be performed, however there are some ambiguous aspects of the methodology such as the definition of co-products and residues (Whittaker et al. 2011). In the calculations the RED does not specify which 'standard conversion values' or emission factors should be used when performing GHG calculations, which may lead to differences in results between tools (Hennecke et al. 2012).

In the business and commerce sectors, the progression to a low carbon economy will require changes in the way organisations deliver goods and services (Carbon Trust 2008). In 2011, the British Standards Institution (BSI) updated the Publically Available Specification (PAS,(BSI 2011)) 2050:2008 methodology (BSI 2008), which presents a consistent approach to accounting for the GHG balance from any product or service (Sinden 2009). Over the last decade there has been an increase in the number of companies that have voluntarily claimed to have committed to GHG reduction strategies following PAS2050. The main driver of this is believed to prepare businesses for future carbon markets where GHG emissions are traded globally (Hall et al. 2010). The process of examining the emissions from a product allows manufacturers to track hot spots and test the relative impacts that in-house decisions have on the GHG impacts of their business (Hall et al. 2010; Plassmann et al. 2010). There is also some evidence that consumers are gradually becoming more environmentally aware, however there remains some confusion to the relevance and impact of carbon labelling schemes (Gadema & Oglethorpe 2011; Schmidt 2009).

Of all economic sectors in the UK, agriculture contributes around 9% of GHG emissions annually (DECC 2012), and is a significant component of the lifecycle emissions of many everyday food and other products. For example, Unilever analysed several products throughout their whole supply chain and found that agriculture is responsible for a significant contribution of the total lifecycle GHG emissions, for example Walkers crisps attribute 36% of the total life-cycle emissions for a bag of crisps to the growing of the potatoes (Pepsico 2012). Agricultural processes also contribute significantly to GHG emissions from 1st generation biofuel supply chains. For example cultivation represents about 32% of total GHG emissions of bioethanol produced from wheat (Mortimer et al. 2004).

Although clearly a significant component of the life-cycle emissions, there are challenging aspects of quantifying GHG emissions from agriculture, forestry and other land uses (McKone et al. 2011). This is due to the dependence of emission on pedo-climatic and management details which are subject to temporal and spatial variations over various scales; leading to significant uncertainty in GHG emission assessments (McKone et al. 2011; Colomb et al. 2012). A clear need has been identified for access to farm relevant GHG calculators which are usable by farmers and land managers but robust and credible enough to be used in supply chain assessments.

2.2. Assessing the environmental impacts of products

The increased awareness of the environmental impacts from agricultural activities has prompted the development of methodologies that account for impacts in a holistic way. Life cycle assessment (LCA) is a technique which has dominated this area of environmental impact assessment as it systematically accounts for all the impacts that arise during the production, use and disposal of a product (Plassmann et al. 2010). The ISO standards 14040:2006 (CEN 2006a) and ISO 14044:2006 (CEN 2006b), describe the main phases of performing a LCA. These include first defining the goal and scope to outline the main aim of the study, such as the functional unit and the final unit of measurement (CEN 2006b). The goal and scope should also provide some detail of the system boundaries of the study. A combination of data collection, iterative analysis, literature review and expert knowledge is required to in order to understand which sources of emissions need to be accounted for in the analysis, and likewise for the inventory phase, as the level and quality of data collected must be sufficient. Finally, the interpretation of the results must reflect back on the original goal and scope of the study, and should only be used according to the intended application of the study.

The 14040:2006 and ISO 14044:2006 state that: “There is no single method for conducting LCA. Organizations have the flexibility to implement LCA as established in this International Standard, in accordance with the intended application and the requirements of the organization” (CEN 2006a). In LCA, methodologies are required to determine the way environmental impacts should be attributed to the final functional unit, including allocation rules that specify how emissions are split between co-products and how these are defined separately from wastes. Without a defined reporting methodology, there are various options to how a LCA could be performed, and it is possible that two studies that examine the same functional unit could both comply with the ISO standards and yet provide a different result. The ISO standards leaves a great deal of scope for interpretation and flexibility to the LCA practitioner (Aylott et al. 2011; Whittaker et al. 2011).

The Intergovernmental Panel on Climate Change (IPCC) provides some specific calculation methodologies for accounting for the GHG emissions for a range of activities that take place in the agricultural (De Klein et al. 2006), energy (Gomez et al. 2006) and transport sectors (Waldron et al. 2006). The IPCC guidelines classify quantification methods into three Tiers. Tier 1 emission factors are relatively straightforward and are derived to be applicable at global or national scale. They tend to 'average out' much of the climatic and geographic variation that nitrous oxide (N_2O) emissions from soil are sensitive to, therefore provide a high-level estimate (Hillier et al. 2011).Tier 2 methods increase the level of detail by employing "smart" emission factors that are specific to particular technologies or regions. Tier 3 methods incorporate increasingly more complicated or involved methods such as process-based models or direct measurement, for example DAYCENT (Del Grosso et al. 2001) or DNDC (Li et al. 2011). Using such tools requires a greater understanding of soil and plant systems compared to using the national default values (Hillier et al. 2011). Therefore, with the Tiered approach, the IPCC offers the LCA practitioner a series of approaches with varying levels of data requirements. This approach is useful where the ease of use has to be balanced against refinement.

2.3. GHG accounting in the agricultural sector

Over the last few years a number of GHG calculators have appeared in the public domain for calculating emissions from either single crops or for whole farms, and many more may have been commissioned by private companies for use "in-house" (N. Mortimer pers. com. 2012). The tools are computational models that contain in-built data that can be manipulated to some extent to provide an individualised account of the GHG emissions for a given crop and user. Other LCA-based tools, such as SimaPro and Gabi can be used, though these require a higher level of input data compared to the GHG calculators discussed here. These tools can be used to provide information on a range of other environmental impacts in addition to GHG emissions, which is necessary to perform a full environmental assessment. A recent review by Colomb et al. (2012) assessed a large number of calculators that are developed for quantifying GHG emissions or mitigation options in agricultural and forestry sector. The authors identified four main types of GHG calculators, those designed to raise awareness, to report, to evaluate projects and to assess products. They discuss how the type of tool will determine the scope of the assessment, including the time and data required and the geographical range and time scale assumed. The Coalition on Agricultural Greenhouse Gases (C-AGG) represents a group of stakeholders who are performing an ongoing review of voluntary GHG reporting methods (C-AGG 2012).

GHG calculation tools are generally used to educate farmers about the main sources of emissions, evaluate mitigation projects, or report emissions to a consumer or certification board (Colomb et al. 2012). The majority of these adopt either a full or streamlined LCA approach to the farm gate, factory gate, or to a final product. Calculation tools can make quite complicated LCA calculations assessable to those with less expertise in GHG reporting (Figure 1). They can also help harmonise calculations to enable more reliable comparisons between products (Hennecke et al. 2012).

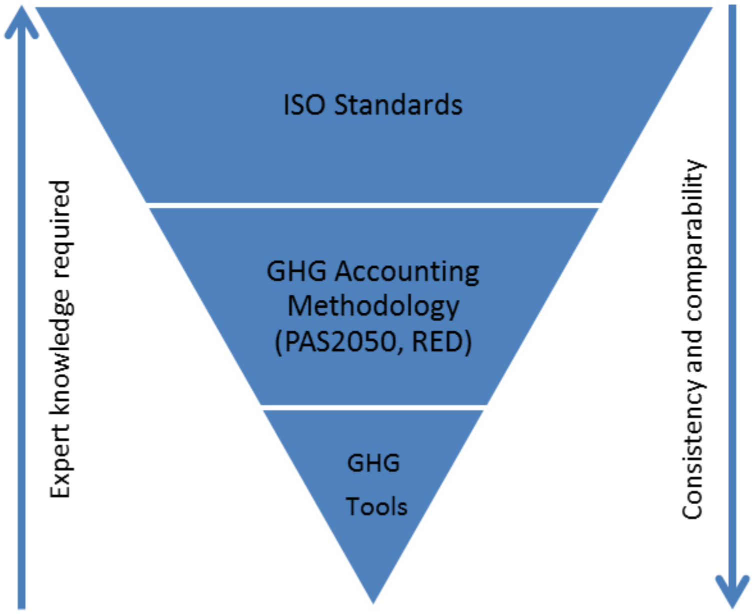

Figure 1 Hierarchy of knowledge requirement and relevance of LCA-based GHG tools for product assessment.

The main aim of a GHG accounting tool is to act as a user friendly interface to bridge input data with a GHG emission impact score. The process of calculating emissions will depend on a series of underlying principles, methodologies, assumptions, and data that are built into the calculation mechanism of the tool (Hall et al. 2010). Calculators are generally less complex than models as they are designed to be used as decision supporting tools for policy makers and project managers, whereas models are oriented for research (Colomb et al. 2012). Both the level of data required by the tool and the type of information generated will depend on the target user. Often, the user is required to perform the data inventory stage; however the goal, scope, accounting methodology and calculation methodology must be determined before a tool is constructed (Aylott et al. 2011). The tools themselves are not methodologies, but facilitate the user to follow the pre-determined methodology.

Therefore, in order to comply with the ISO standards a tool should clearly define the goal and scope, or purpose of the tool. As GHG calculators are increasingly being used for decision making (Aylott et al. 2011) it is important that they are fit for their original purpose, but also used in an appropriate way.

2.4. Scope and outline

This study identifies carbon foot-printing tools for calculating the carbon or GHG emissions from agricultural products. The research focuses on GHG emissions arising from the cultivation phase. An example inventory data set from a typical feed wheat crop is used. Wheat is selected as it is the most extensively grown food crop in the UK (DEFRA et al. 2010), and in the context of biofuel production wheat is likely to be used for bioethanol production than other crops due to its lower nitrogen fertiliser requirements (Clarke et al. 2008).

3. Methods

3.1. Review of existing accounting tools

A desk-based review was performed to identify existing greenhouse gas calculation tools (sometimes referred to as 'carbon tools'), available in the public domain. This review focusses on tools applicable to the UK only, as the geographical range may affect the specificity of the tool (Colomb et al. 2012) and may be populated by country-specific emission factors. Methodologies and reporting protocols were excluded from the analysis. Tools specific to calculating emissions from crop cultivation in the agricultural or bioenergy sectors were included in the study. This could be in the context of the whole supply chain of a final product, or from a whole farm. The main focus of the bioenergy tools was calculating the GHG emissions from biofuel production. Although there are many tools that calculate emissions from dairy and meat production, there are particular issues that arise with managing livestock, and therefore these should be reviewed in a separate study. Likewise, studies that focus on management of woodlands and forests can also be reviewed in a separate study.

3.2. Multi-criteria-analysis of relevant accounting tools

Tools that are available in the public domain and represent crops grown in the UK were selected for further review (Table 1). For tools that focus on biofuel supply chains only those where the agricultural stage can be studied in isolation were included. Tools designed to model specific processes within a supply chain were considered to have a too narrow scope for addressing the full emissions for a crop, and are excluded.

A multi-criteria-analysis (MCA) was performed, following the methodology described in Hall et al. (2010), to test for relative weaknesses and strengths in the tools identified. Some criteria from Hall et al. (2010) were used, though most were developed to objectively assess each tool whether they were a) user friendly b) informative c) transparent and d) comprehensive (see Appendix 1). Comprehensiveness was based on whether or not the tool includes the farm inputs that most sensitively affect the GHG emissions from a crop. The analysis did not necessarily assess the accuracy of the results, as this may be open to debate without the appropriate experimental data available to determine accuracy. These include land use change (LUC), nitrogen fertiliser manufacture and application to soil, diesel fuel consumption and to a lesser extent other fertilisers and pesticides (Roches et al. 2010; Röös et al. 2010). Using IPCC Tier 1 emission factors was regarded as a suitable baseline to account for N_2O emissions from fertiliser, crop residue incorporation and manure application, and tools applying this were given a comprehensive score of 2. Those adopting a higher Tier approach (2 or 3) were rated higher. Irrigation was also identified as a major source of GHG emissions (Roches et al. 2010) though this represents just 2% of crops in England (National Statistics 2011). Drying is excluded as this may fall outside the scope of ‘to the farm gate’ and is a typically a minor source of GHG emissions (Roches et al. 2010). Following the approach by Hall et al. (2010), the categories were kept separate as not to imply they are equally weighted in importance in performing a GHG assessment of wheat. The criteria were assessed according to four levels of relevance (Table 2), and each tool was given a total score for each category.

3.3. Application of calculation tools to a case study

Whitaker et al. (2010), identifies three main causes of variation in LCA studies of agricultural, namely biofuel production systems: ‘real’ variation due to input data, ‘methodological variation’ due to different allocation methods, and ‘uncertainty’ in the emissions that occur due to inputs or processes. To eliminate ‘real’ variation, the results generated by the selected tools were compared ‘to the farm gate’ using a model set of input data for feed wheat cultivation. This paper therefore examines whether variation is due to the systems boundaries, or the emissions factors assumed within the tool. LUC of grassland and forestland to arable land is also examined separately as this may dominate the GHG emissions (Roches et al. 2010). The dataset listed in Table 3 represents the total amount of data required by the least and the most ‘data demanding’ tools. The data are based on typical examples taken from growers guides and from literature. Fertiliser N is provided by a combination of ammonium nitrate (60%), urea (39.5%) and farm yard manure (0.5%, FYM) to test whether tools differentiate between different N sources. The relevance of the input data was not the main focus of study, rather the differences in the calculated emissions when the same input data are used in each tool. To eliminate methodological variation, the final emissions were based on a ‘per hectare’ basis, assuming that all straw is incorporated into the soil. Therefore, any differences in how emissions are allocated between wheat and grain were not observed.

4. Results and discussion

4.1. Desk-based review

The desk-based review identified 31 resources that can, in some way, be used to calculate the emissions from crop cultivation, or from a specific aspect of crop production (Appendix 1). Sources originated from commissioned work to environmental consultancy groups, from governmentally and non-governmentally funded organisations, programmes developed from scientific research in Universities and from certification schemes. Eleven of these resources were selected for further review (Table 1).

Of the 31 resources, 15 were excluded as they are based in the United States (6), Australia (5), Europe (2), New Zealand (1) and Canada (1). Seven of the resources were process-based modelling software that could be applied to the UK (Appendix 2); and were excluded as they are typically used to examine specific processes in the soil. CPlan has two developed two tools, however the more recent version (CPLANv2) is not free to use. The Carbon Trust Carbon Footprint Expert Tool ® (Carbon Trust 2012) was also excluded from further review as this is only available to consultancies for a fee.

In the 11 tools selected, 6 are designed in order to calculate the emissions on a farm-level and 5 examine cereal cultivation as part of the bioethanol production pathway, therefore they represent a combination of tools designed to raise awareness, and to report GHG emissions on a farm and product level. All of the tools require data input that would all be known by any farm owner or manager. There are large differences in the system boundaries of the tools, and these are listed in the supporting material in Appendix 1.

The main aim of the majority of the farm-based tools is to educate farmers as to where emissions occur on their farm (Muntons.com 2012) and identify GHG mitigation options so that they are in a position to accept future GHG emission reduction challenges (C-Plan 2007). This can be for marketing, economic or ethical reasons or to understand how they can adopt practices that lead to better quality soils (CFF 2009). This is to some extent, a similar goal of the bioenergy-based tools; except they are focused on accurately measuring the GHG balance of various stages of the biofuel supply chain. The Biograce, RSB and RFA Tools are specifically produced to aid biofuel producers calculate their GHG balance according to the reporting methodology laid out in the RED. Both the RSB's own methodology and that detailed in the RED are examined here. The following sections discuss how the goal and scope of the tools affects the structure and function of the tools.

4.2. Multi-criteria-analysis and the goal and scope

The MCA showed differences between the tools for each of the four categories assessed (Table 4). Across the four categories, the averages differed between farm and bioenergy-based tools (Table 4). Farm tools achieved a higher score for 'user friendliness' and the bioenergy tools were generally rated more informative, comprehensive and transparent.

In terms of user friendliness, the highest rating tools were the CFF and CCalc Tools (78%), followed by the Cool Farm Tool and the HGCA tool (72%). These tools were rated accordingly due to ease of access, intuitiveness, flexibility of input units and support and guidance for using the tools. Poorer performing tools were lacking instructions, required a password or installation and lacked flexible or non SI units. In the 'informative' category the majority of tools were high scoring. The highest rating tool was the Cool Farm Tool (100%), mainly because it provides results in various formats and with a breakdown of all emission sources. Less informative tools did not provide a clear enough breakdown of emissions.

The highest rated tools in terms of transparency were the Cool Farm, BEAT and RSB Tools. The Cool Farm and BEAT Tools permit the user to access the original Excel-based calculations, including referenced sources of emission factors. The RSB Tool does not provide an Excel-based model, although the manual is highly transparent. Lower ranking tools did not provide sufficient details of the types of emission sources included in the analysis, or provide details on the sources of emission factor data. The most comprehensive tools assessed were the Cool Farm and RSB Tools, as these included LUC and adopted Tier 3 IPCC methodology. LUC was included in 6 out of 11 tools, and these were given a higher rating as LUC can potentially dominate GHG emissions in agricultural LCAs (Roches et al. 2010). The least comprehensive tools were those that did not specify whether they include N fertiliser manufacture and/or application, or did not state which N_2O sources were included. Only BEAT included some aspects of uncertainty.

The results of the MCA in some way reflect the main goal and scope of the tools. As it is more likely that farm-based tools will be used by non-LCA practitioners there is a level of user-friendliness expected (Colomb et al. 2012). Bioenergy-based tools are generally used by LCA practitioners, or those with expertise in the industry to assess whether a biofuel has reached its GHG saving target. These tools therefore demand a greater level of information, transparency and accuracy.

The main goal of some of the farm-based tools is to provide a calculation platform to educate farmers about GHG emissions occurring due to their activities and choices of management. Therefore the scope of these tools is the measurement of GHG emissions that occur on whole farm perspective and not necessarily a single crop. These tools require information on all site inputs and fuel use, as well as other farm-based activities such as woodland sequestration. Tools that work on a single crop level, such as the Muntons and Cool Farm Tool, require information on all site inputs attributed to a single crop.

In bioenergy-based tools the goal and scope is to accurately assess the GHG savings compared to using conventional fossil fuels. For example, the Biograce Tool was developed in response to the introduction of the RED, which sets specific GHG reduction targets over a set of timescales that must be met. The higher demands for accurate reporting of GHG emissions from biofuel production may explain why these tools score higher on the informative, transparent and comprehensive categories in the MCA.

4.3. Comprehensiveness and the systems boundaries

Figure 2 demonstrates the overall emission profile generated by each tool, based on the input data in Table 3. The emissions from LUC are examined separately. The results demonstrate variation in both the magnitude of the estimated GHG emissions per hectare and the emission sources included in the analysis. The only emission source consistent in all tools is diesel fuel consumption. The system boundaries are closely linked to the comprehensiveness of the tools, as this considers which major sources of emissions were included in the calculations: tools lacking major sources of emissions were scored low in comprehensiveness. It is important to note here that comprehensiveness does not necessary imply accuracy.

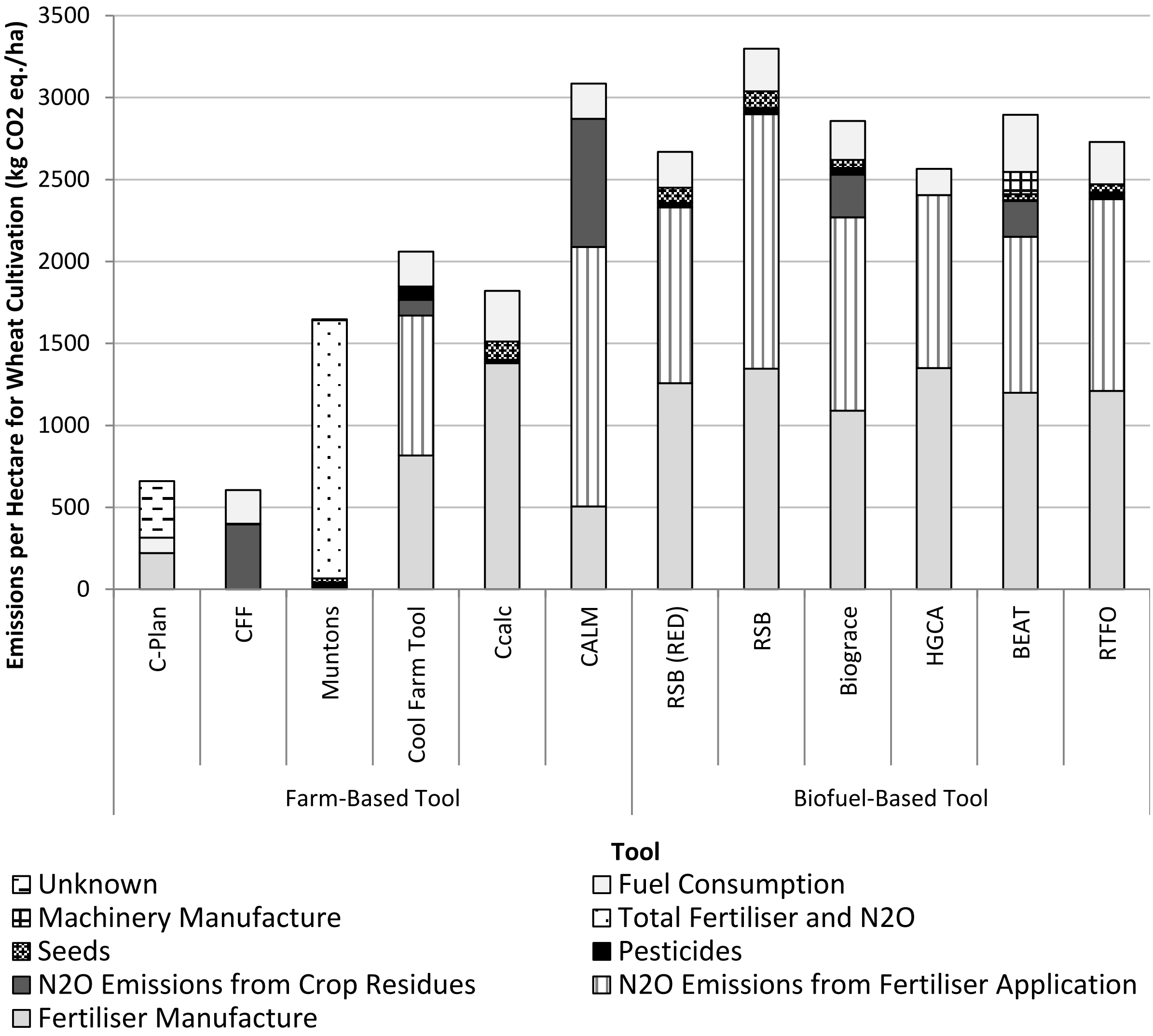

Figure 2 Emission profile from each GHG accounting tool for 1 hectare of wheat cultivation.

Four out of the six farm-based tools have a goal to 'accurately measure the GHG emissions from a farm'; however the 'comprehensiveness' score from the MCA suggests this goal is not achieved. Overall, on a per hectare basis, the total GHG emissions ranged between 606 and 3298 kg CO_2 eq. The average emission result calculated by all tools is 2239 kg CO2 eq./ha, where the average for the farm tools (1642 kg CO2 eq./ha) is almost half that of the bioenergy tools (2836 kg CO2 eq./ha). This is mainly due to the lower results calculated by the C-Plan and CFF Tools. It is difficult to determine why these tools calculate lower GHG emissions, due to their lack of transparency. These tools also scored a relatively low score in comprehensiveness: the CFF Tool achieved the lowest score (10%) as it has apparently excluded N fertiliser manufacture and N_2O emissions from soil, which account for an average of 43% of emissions in the tools that include them. The C-Plan Tool was rated low (20%) due to both a lack of detail on which GHG emission sources are included, for example whether they include direct, indirect N_2O emissions or those from crop residues, and also because their estimate for fertiliser production and application is lower than expected when using IPCC Tier 1 emission factors (Figure 3). This tool has a separate entry for 'crops' in the results; however it is not clear what this specifies. Both the CCalc and Muntons tools have also been penalised in the comprehensiveness score due to the level of detail that they provide on N_2O emissions from soil.

There are various sources of emissions from soil (Figure 3), whether these are from direct or indirect N2O emissions from N fertiliser application, or N2O from crop residue incorporation or manure application, or CO_2 emissions from lime or urea hydrolysis (De Klein et al. 2006). The variation in the emission estimates observed may be due to the IPCC Tier applied (Colomb et al. 2012), or due to the incompleteness of the N_2O calculations where there is a lack of knowledge of the various sources, or a combination of both. Figure 3 indicates which tools calculate an emission result similar to that expected by the IPCC, suggesting that all sources of N_2O are included in their system boundaries. In many cases therefore, the issue of transparency and comprehensiveness could be improved if details of the system boundaries of the tools were stated on the tool developers' websites or manuals. Alternatively, tools should provide disaggregated results for emissions from soils.

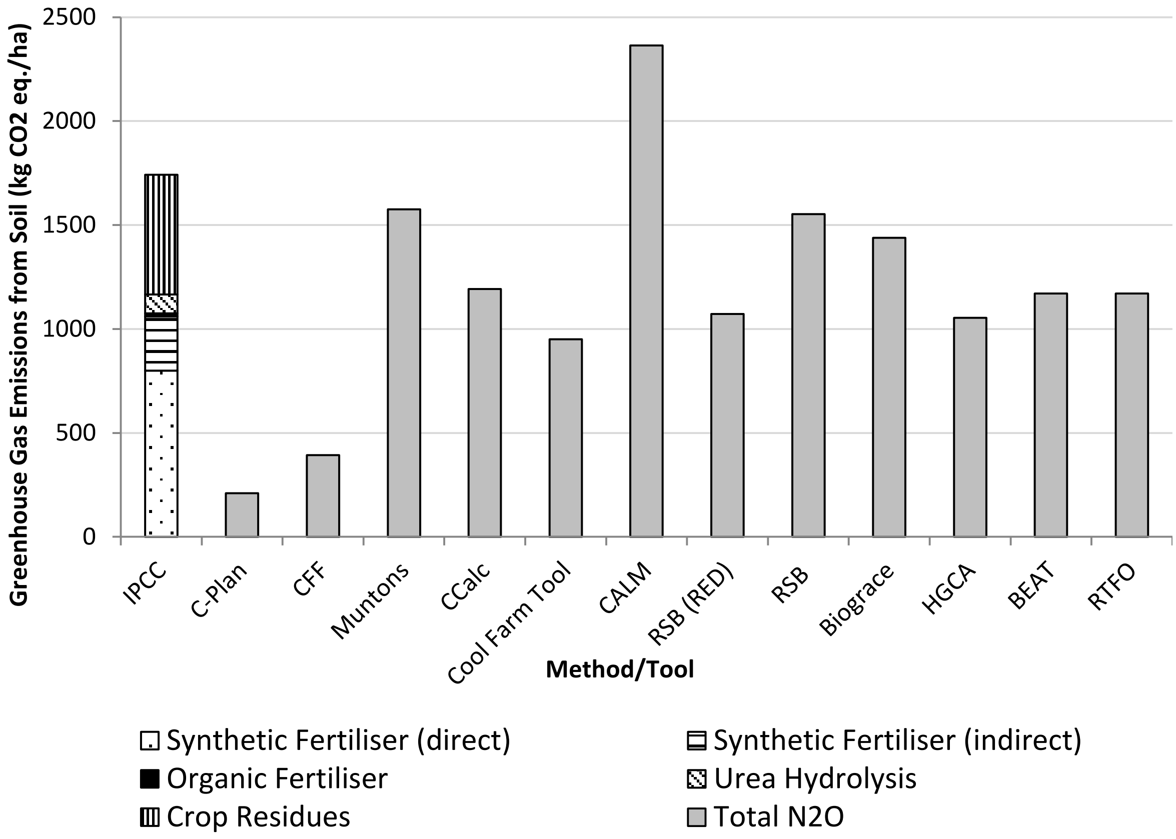

Figure 3 Expected and observed GHG emissions from soil due to fertiliser application (based on data from Table 3).

Four tools did not include details on LUC (C-Plan, Muntons, HGCA, and BEAT). Those that do provide varying estimates for LUC, though this range is greater for LUC of forestland to arable land (Figure 4). The order of magnitude of GHG emissions from wheat ranges between 606 and 3298 kg $CO_{2\ eq.}$/ha, whereas LUC ranges between 1918 and 7000 kg $CO_{2\ eq.}$/ha or 4147 and 27000 kg $CO_{2\ eq.}$/ha for grassland or forestland conversion to arable land, respectively, therefore the range of potential impacts of LUC are highly uncertain, but overly large. The tools estimate different GHG implications of LUC, despite the Cool Farm Tool, Biograce and RSB Tools using the same original resource to calculate emissions (Bickel et al. 2006). This states that LUC carbon losses should be based on any land conversion that has taken place in the last 20 years and is dependent on the type of LUC occurring (Bickel et al. 2006). This methodology is also followed by the Commission Decision 2010/335/EU (EC 2010), which users of the Biograce and RFA Tools are instructed to use. The Cool Farm Tool follows the IPCC to model specific LUC changes for over 113 countries (Hillier et al. 2011).

The CALM Tool does not state the specific source of calculations; though it appears to produce a similar result to the Cool Farm Tool (Figure 4).

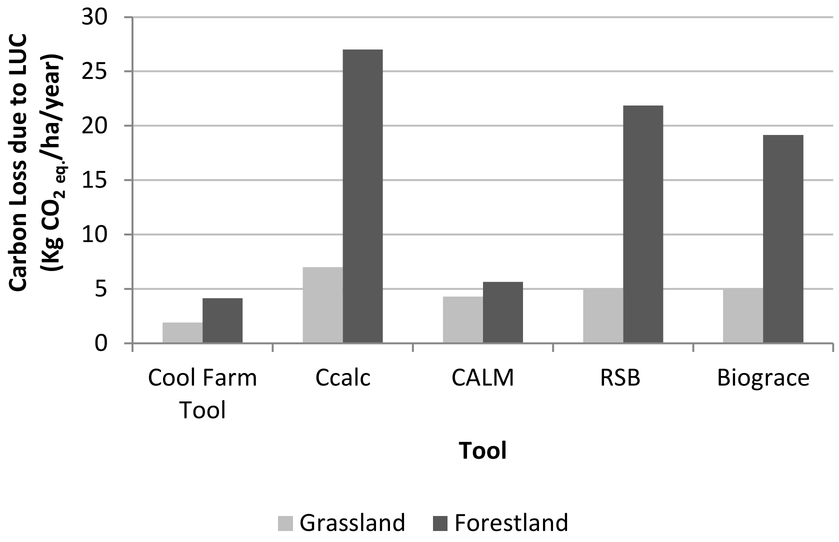

Figure 4 Variation in estimates for LUC from grassland and forestland to arable land.

For data entry of details of LUC, some tools require a selection of 'before' and 'after' land uses, whereas some require more details on the soil type, geographic zone and changes in how the site is managed. Out of the 7 tools that include LUC, the majority provide default drop-down menus as well as offering the user-defined inputs. Both the Cool Farm and RSB Tools provide a detailed calculation tool for LUC, including changes in tillage, inputs and residue management. The RSB Tool does this, although in a generally less user-friendly manner. Though it is outside the scope of this paper to determine the accuracy of LUC estimates, it is clear that the Cool Farm Tool offers both the most comprehensive and most accessible calculations for LUC for a non-LCA practitioner to use, though if the user can calculate their own LUC estimate then all tools that offer this function are appropriate.

Uncertainty was clearly lacking in the majority of the tools, as only BEAT included some indication on how the result may range. The CCalc Tool requires the user to define the level of data quality, but it does not appear to be referred to in the results. Also, none of the tools provide an account of which sources of GHG the final results are most sensitive to, but these are known from literature (Roches et al. 2010). An absence of uncertainty suggests a lack of comprehensiveness as this can provide some information on the robustness of the data sources used and detail any temporal or spatial uncertainty (Guo & Murphy 2012). In this study, the uncertainty mainly lays with the emission factors that the tools use, as the input data will be provided by the user based on records or measurements (Colomb et al. 2012). Even where the IPCC calculation methodology has provided an emission range of 0.3 to 3% kg N_2O-N/kg N applied for artificial N application to soil (De Klein et al. 2006), most tools appear to select the default of 1%. It is suggested that tools that adopt higher Tier IPCC approaches, such as the Cool Farm and RSB Tools, reduce the uncertainty in their results compared to using IPCC defaults (Guo et al. 2011), yet the actual uncertainty is not presented. Providing a single result, rather than a range or level of uncertainty, is limited in that it will only give users an indication of the average GHG emission for their crop, or a baseline from which mitigation projects can be compared.

GHG emissions from farm machinery are some minor sources of emissions that are included in some tools and not others. The CFF tool attributes the total GHG emissions from manufacture of farm machinery to the year in which the user provides information for; therefore these are overestimated. This is a consequence of the tool accounting for the farm-level emissions over an unspecified period of time, rather than the emissions for one year's work. In this study, the emissions for farm machinery construction were readjusted so they are allocated temporally to the time required to cultivate and harvest one hectare of wheat (Table 3) and it is assumed that the machinery has a working lifetime of 7000 hours (EcoInvent 2007). The guidelines for the CFF Tool state that after 10 years an item has 'paid off its carbon debt' meaning that the emission from manufacture do not need to be included, therefore farmers should use older machinery when possible (CFF 2009). This logic is somewhat misguided, as although maximising the use of life of an item will reduce the relative emissions for 1 hour's work, older machinery is less likely to be fuel efficient and conform to current emission standards. When allocated correctly to the crop level the contribution of farm machinery construction is low, as is also found in BEAT and the RSB (Figure 2).

The RSB also includes this source of emissions, though not when applying the RED methodology (RSB 2012), as this specifically excludes emissions from building and machinery construction.

The emissions from animal manure are usually minor, depending on the quantities used. Four tools (C-Plan, CFF, CCalc and BEAT) included the emissions from manure delivery, though the majority excluded this. These may be excluded from the calculations as they are a relatively minor source of emissions, compared to artificial fertilisers. Four tools (HGCA, CALM, RSB and Cool Farm) account for N_2O emissions due to manure application, whereas these are apparently excluded from the others, though there is generally insufficient transparency in which to determine this fully. Some justification of this exclusion is that the N_2O emissions are attributed to the meat sector, in the waste disposal phases of animal husbandry. The tools that exclude emissions from manure may assume that the emissions are accounted for in the meat sector. The IPCC calculation methodology specifies, however, that all manure and organic fertiliser application should be attributed to the crop that receives it for fertilisation purposes; therefore this should be included in all tools.

In summary, the comprehensiveness of the bioenergy tools is better scoring than the farm tools and shows a higher level of homogeneity in the results. One possible explanation for this is that there are currently some existing GHG reporting methodologies in the biofuel sector, and biofuel producers are obliged to report on their emissions. The PAS2050 methodology is applicable to the food and agricultural sectors but it is currently voluntary. The RED policy in the biofuel sector differs to the PAS2050 at the field-level (Whittaker et al. 2011). The methodology outlined in the RED underlies the calculation methodology in the Biograce, RSB and RFA Tools. The comprehensive score for the RFA Tool is comparatively lower as it does not differentiate between fertiliser types, lacks N_2O from crop residues and uses IPCC Tier 1 emission factors. The HGCA and BEAT Tools were developed before the RED or RTFO were established and achieved lower comprehensiveness scores. Therefore there is evidence that since then, GHG accounting methodologies and awareness of sustainability issues has aided the development of tools that provide a more comprehensive account of GHG emissions from cultivation.

4.4. Transparency and emission factors

Transparency was assessed according to the accessibility of the inbuilt emission factors and calculation methodology, therefore this is somewhat linked to comprehensiveness. Transparency provides the user to identify the data sources used and calculation methodologies followed so that their quality or relevance can be assessed or scrutinised. Some tools provide details of the calculations, whereas some could be described as 'black boxes' where only the inputs and outputs are visible (Carvalho et al. 2012). Overall, the bioenergy-based tools achieved a higher transparency score (67%) than the farm-based tools (49%). This may also be a result of the goal and scope of the two types of tools: farm-based tools are more likely to be used by non-LCA practitioners, whereas bioenergy-based tools are designed to be used by those with expertise in LCA.

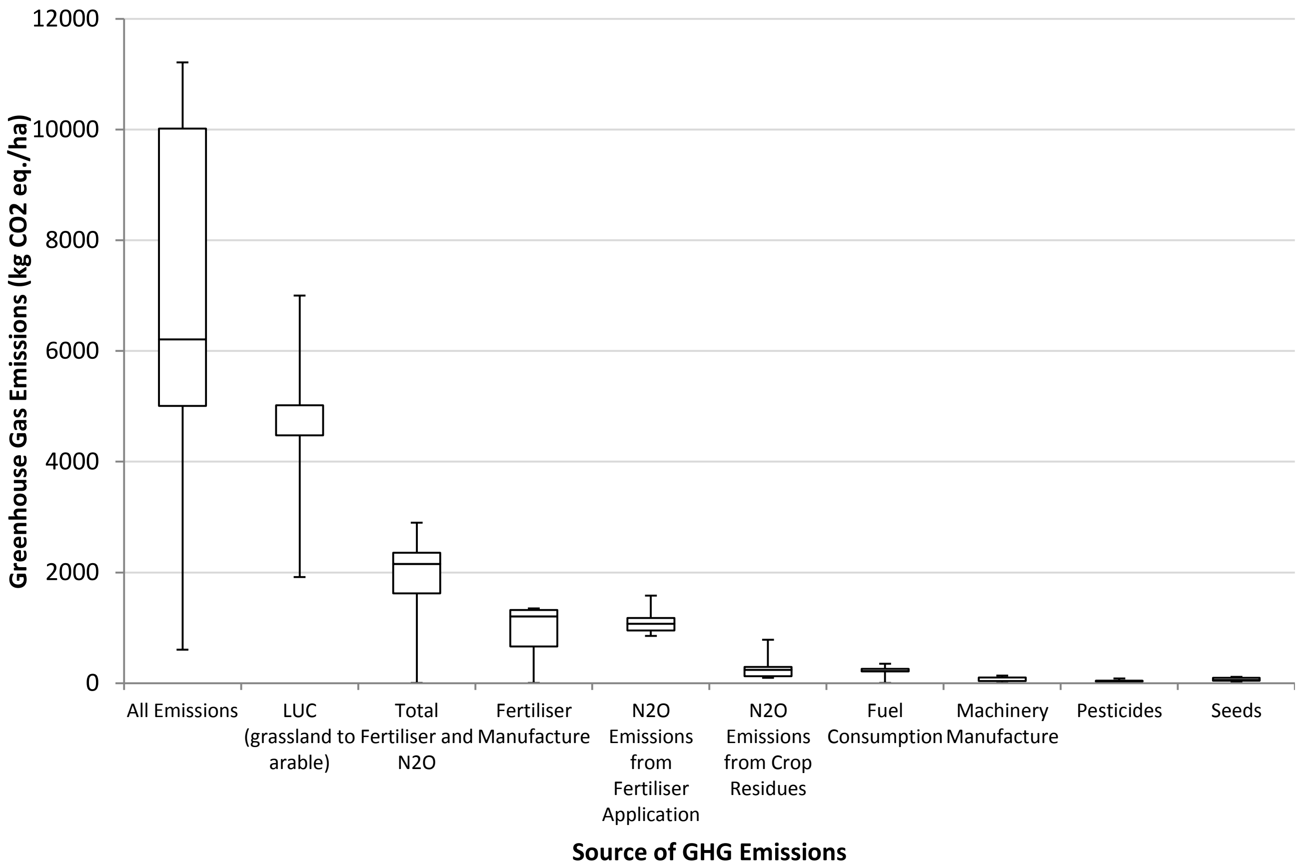

Figure 5 A quartile box-plot showing sources of variation in the overall emissions for wheat cultivation.

A recently published study compared the GHG emissions calculated by the Biograce and RSB Tools for a number of biofuel supply chains and showed that they produce different results despite them both complying with the RED methodology (Hennecke et al. 2012). The differences are due to different emission factors used for fertiliser manufacture and N_2O emissions from soil, and estimates for LUC differ across tools, particularly for conversion of forestland (Hennecke et al. 2012). A similar result is found here (Figure 5). The sources of emission factors for fertiliser manufacture differ across tools (Table 5); therefore the overall result is highly sensitive to the data sources used. Only 4 of the 11 tools provided separate emission factors for ammonium nitrate and urea, despite that emissions from ammonium nitrate are approximately 67% higher than urea (Brentrup & Palliere 2008). The importance of harmonised emission factors in GHG calculation highlights a policy and methodological gap that should be addressed in future tools and methodologies (Hennecke et al. 2012).

As mentioned in Section 3.3, the estimated N_2O emissions from soil vary between the tools (Figure 3); and this is also a major cause of variation in the results (Figure 5). The general lack of transparency means that it is difficult to determine why this occurs. Many of the tools state that they follow IPCC Tier 1 emission factors, and few have applied Tiers 2 or 3, though the details of the calculations are not transparent. It is suggested that a Tier 3 approaches are more appropriate for accurately assessing N_2O emissions from a particular site (Whitaker et al. 2010), and this is adopted by both the Cool Farm and RSB Tools. This involves utilising modelled emission factors that are specific to the country and are validated through experimental measurements (De Klein et al. 2006). The Cool Farm Tool utilises emission factors on specific soil parameters and on specific fertiliser types (Hillier et al. 2011; Hillier et al. 2012). The RSB calculations are based on Ecoinvent (Nemecek et al. 2007) when following the RSB methodology, or the IPCC (Tier 2) when following the RED methodology (De Klein et al. 2006). Figure 3 demonstrates that although a Tier 3 approach is adopted, there is still variation in the calculated emissions. Therefore some validation of the most appropriate IPCC Tier 3 emission factors may be required for purposes of harmonisation, and it is expected that these emission factors will depend on location. It is expected that, by 2014, a series of UK regional maps of local N_2O emission factors will be developed (Whitaker et al. 2010) which may facilitate a more consistent approach between tools.

There is also a lack of transparency with regards to N_2O emissions from crop residues also contribute to the overall GHG emissions from wheat cultivation (Figure 3). These were clearly included in 6 of the 11 tools and the magnitude ranged between 96 and 782 kg CO_2 eq./ha, or between 5% and 33%. The RSB Tool includes this source of emissions but does not report separate information on this. Some tools require the user to specify the fate of straw, i.e. how much was incorporated or removed. Where the yield of straw is not specified by the user, the tools may estimate this using the

IPCC (Table 11.2, De Klein et al. 2006). BEAT assumes that straw is removed from the site, and the emission estimate for crop residue incorporation represents stubble incorporation. Differences in this aspect of the calculation may be a cause of the variation of the results. **Error! Reference source not found.**

In summary, transparency varies across tools and there is evidence that the majority of the variation in GHG emissions is caused by fertiliser manufacture and N_2O emissions, which represent over 60% of total emissions in those tools that include them (Figure 5). There is evidence that the estimates for GHG emissions from fertiliser manufacture vary because the tools use different references (Table 5). Estimates from LUC can also range considerably, particularly for forestland conversion; but this is excluded in some tools. The variation in crop residues is due to the assumptions made on the yield of straw being ploughed into the soil. GHG Emissions from fuel consumption vary little across tools. There is also minor variation in the final results due to machinery manufacture, pesticides and seeds.

4.5. Implications of results

This study has demonstrated that a number of tools available in the public domain have the ability to calculate the GHG emissions from the same process, yet can provide very different results. Some of the selected tools appear to either exclude or incompletely calculate some major sources of GHG emissions, particularly LUC and N_2O emissions from soil, therefore their credibility is questionable (Whitaker et al. 2010).

One potential implication of this is that some tools may be misused and used to calculate GHG emissions for activities that they are not designed for. For example, farm-based tools that are designed to calculate GHG emissions on a farm level will require information on various aspects of farm management that may exceed what should be attributed to a specific crop. It can become difficult to attribute GHG emissions farm activities to the production of a given 'tonne of wheat'. As this is not the original goal and scope of the tool, they should not be used in this way. An exception is the Cool Farm Tool, which can be used to calculate the GHG balance of a single crop, or a single crop farm, and is one of the most highly rated tools observed in this study. It is possible that other tools that are not in the public domain, or available in the future, could also be suitable for GHG accounting in agriculture.

Using a bioenergy tool to estimate the GHG emissions from a given crop may be more difficult to perform by a non-LCA practitioner, as these tools are generally less user friendly. Bioenergy tools are designed to assess the GHG emission savings of a biofuel against strict targets. Hennecke et al., (2012) highlights that if biofuel producers have an option of tools to calculate their GHG emissions, then it is likely they may select a tool that generates the greatest GHG savings. Even when the tool complies with the RED, differences in the emission factors may yield different results.

5. Conclusion

"All models are wrong, but some are useful" (Box 1976). As models are built from a combination of methodology, data and informed assumptions, any differences will naturally give different results, but sometimes there are no right or wrong answers, just a reflection of a different perspective on how to calculate the emissions (Aylott et al. 2011; Aylott et al. 2012). Both the farm and bioenergy tools can be used to calculate the same thing (i.e. one hectare of wheat); yet after comparing some tools that are available in the public domain, they appear to produce very different results.

GHG calculation models that follow a LCA approach require careful planning so that the model is fit to fulfil its original goal and scope. A tool designed to provide a comprehensive account of the GHG emissions from crop production for food or for biofuel production should include emissions from soil and fertiliser manufacture in the system boundaries, as these represent approximately 80% of total emissions. Tools excluding these from the system boundaries will not provide a full account of the emissions resulting from arable cropping, therefore they should be avoided. LUC is also another important source of GHG emissions that should be included in any GHG calculator that utilises land.

Suitable GHG calculator tools include those that present both a user-friendly platform for use, and provide a comprehensive account of GHG emissions occurring on a farm or product level. This study identified the Cool Farm Tool as the most highest-rated tool that is available in the public domain and free to use. This is recommended for use for single crop assessments. For whole-farm assessments the CALM Tool is recommended. For biofuel assessments that are RED-compliant, the RSB Tool or Biograce are recommended.

In terms of the actual GHG estimates, emissions from LUC are the largest sources of variation, but this was not featured in all tools. After this, N_2O emissions from soil and fertiliser manufacture are also significant sources of variation between the results calculated. As transparency is lacking, it is difficult to determine whether this variation is a result of the system boundaries or the calculation methodologies employed. The variation in fertiliser manufacture is due to a combination of data sources used by each tool. As fertiliser manufacture is typically a major contributor to total GHG emissions from an arable crop, small differences in the emission factor can generate very different results.

This study found that farm-based tools are more user-friendly than bioenergy-based tools; though the latter achieved a higher rating in the level of information provided in the results, the transparency of the underlying assumptions and the comprehensiveness of emission sources included in the calculations. An exception to this is the Cool Farm Tool, which was the highest rated. The differences in scoring between the selected farm and bioenergy tools may be due to their original goal and scope: farm-based tools are generally designed to inform users on the sources and mitigation options on a farm level; bioenergy-based tools provide information on the GHG emissions from producing a single crop. The differing goal and scope of the two approaches may affect the design of the subsequent GHG calculation tool, and hence the results.

This study has demonstrated that different goal and scopes, system boundaries and underlying emission factor data within GHG calculation tools can result in very different results despite the same input data used. The goal and scope of a tool is the most important factor in determining its intended use. Bioenergy-based tools demonstrated less variation across the results than farm-based tools, which may be due to the methodological guidelines available for biofuel reporting. Therefore, there is a need to harmonise both methodology and emission factors in biofuel GHG calculation tools, so that at least a consistent result can be generated.

6. Acknowledgements

This analysis is based on the versions of the calculation tools listed in Table 1, or those that were accessed online in the year 2012. Future versions of the tools need to be reassessed. The authors would like to thank the reviewers of the original submission for their very helpful comments. The authors would also like to thank Dr Jon Hillier from Aberdeen University for his useful comments on the Cool Farm Tool. They would also like to thank Dr Nigel Mortimer from North Energy Associates for a useful discussion on the RED methodology and GHG reporting methodologies. They would also like to thank Jan Dick for help with the C-Plan Tool. Carly Whittaker would like to thank the University of Bath for funding her PhD studentship. The contribution of Dr Marcelle McManus is partially funded by the UK Biotechnology and Biological Sciences Research Council's (BBSRC) Sustainable Bioenergy Centre (BSBEC), under the programme for 'Lignocellulosic Conversion to Ethanol' (LACE) [Grant Ref. BB/G01616X/1]. This is a large interdisciplinary programme and the opinions expressed in this paper are those of the authors alone, and do not necessarily reflect the views of the collaborators or the policies of the funding bodies. PS is a Royal Society-Wolfson Research Merit Award holder.

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Tables

Table 1 List of GHG accounting tools included for further review

Producer	Tool	Access	Brief Description	Final unit of measurement	Website/(Reference to Tool/Manual)
Farm-Based Tools					
Country Land and Business Association	CALM	Online	Farm-based GHG reporting	Whole farm	http://www.calm.cla.org.uk (CLA 2008)
SEE 360 Ltd	C-PLANv0	Online	Farm-based carbon reporting	Whole farm	http://www2.cplan.org.uk (C-Plan 2007)
Manchester University	CCalc	Download spread sheet	Carbon calculator of LCA emissions along supply chains	User defined	http://www.ccalc.org.uk (CCaLC 2012)
Climate Friendly Food	Organic Farmer Carbon Calculator	Online	Farmer and growers carbon calculator	Whole farm	http://cffcarboncalculator.org.uk/carboncalc (CFF 2009)
Cool Farm Institute	Cool Farm Tool v1.1	Download spread sheet	Greenhouse gas calculator for farming	Whole farm/ 1 hectare of farm/ 1 tonne of crop	http://www.coolfarmtool.org (Hillier et al. 2011)
Muntons	Muntons barley calculator v4	Download spread sheet	Barley carbon calculator	1 tonne of crop	http://www.muntons.com/ (Muntons.com 2012)
Bioenergy-Based Tools					
Biograce	Biograce calculatorv v4b	Download spread sheet	Harmonisation of biofuel calculations	hectare of crop/MJ bioethanol	http://www.biograce.net/ (Biograce.net 2012)
Renewable Fuel Agency	RFA - RTFO Carbon Calculator v1.0	Download programme	Biofuel carbon calculator	hectare of crop/tonne/ MJ bioethanol	http://www.dft.gov.uk/publications/carbon-calculator/ (Westphal et al. 2007)
North Energy	Biomass	Download	Biofuel supply chain GHG	hectare of	http://www.biomassener

Associates and AEA Technology	Environmental Assessment Tool (BEATv2)	programme	assessment	crop/1000 litres bioethanol	gycentre.org.uk/ (AEA Technology & North Energy Associates 2008)
Round Table of Sustainable Biofuels	RSB Tool	Online	Individual stages of supply chain	hectare of crop/MJ bioethanol	http://buiprojekte.f2.htw-berlin.de:1339/welcome (RSB 2011; RSB 2012)
Home Grown Cereals Authority	HGCA Biofuel GHG Calculator	Online	Biofuel GHG calculator	tonne/ litre/ GJ of bioethanol	http://www.hgca.com/content.output/2135/2135/Resources/Tools/Bioethanol%20Greenhouse%20Gas%20Calculator.mspx (Woods et al. 2005)

Table 2 Example of the MCA criteria and scoring.

Criteria	Score			
	3	2	1	0
User Friendliness				
Is the tool readily available?	Yes- Online or ready to download	Yes - but requires installation	Yes- but requires permission /password	Not available
Is support available?	Yes- A support telephone number	Yes - A support email address	Less obvious	None
Are manuals provided?	Yes - Detailed with data collection guidance	Yes - detailed manual	Basic instructions	None

Table 3 Example for site input data for cultivation of wheat.

Input	Type	Amount	Units	Reference
Site Establishment	Ploughing (diesel)	28.3	litres/ha	(Williams et al. 2006)
	Power Harrowing (diesel)	17.9	litres/ha	
	Planting (diesel)	8.3	litres/ha	
	Rolling (diesel)	2.2	litres/ha	

	Spraying fertilisers (diesel)	5.4	litres/ha	Assume performed 3 times (Nix 2011), fuel consumption from (Williams et al. 2006)
	Spreading manure (diesel)	9.7	litres/ha	(Lal 2004)
	Total Diesel (per hectare)	71.8	litres/ha	
Fertiliser	Urea (46.4% N)	123	kg/ha	Total N demand for feed wheat (Nix 2011)
	Ammonium Nitrate (34.5% N)	330	kg/ha	
	Cattle Slurry(3% N)	633	kg/ha	
	(Total N)	190	kg N/ha	
	Phosphate	60	kg P/ha	(Nix 2011)
	Potassium	43	kg K/ha	(Nix 2011)
Pesticides	Herbicide	1.3	kg a.i/ha	(Garthwaite et al. 2010)
	Fungicide	1.4	kg a.i/ha	
	Insecticide	0.01	kg a.i/ha	
	Growth Regulators	1.1	kg a.i/ha	
	Total Pesticides	3.81	kg a.i/ha	
Seed	Wheat grain	175	kg/ha	(Nix 2011)
Harvesting	Combine Harvester (diesel)	20	litres/ha	
Machinery Used	Tractor (150hp)	To power the following:		(Williams et al. 2006)
	Plough, 1m	1.2	hour/ha	
	Power Harrow, 4m (PTO powered)	0.8	hour/ha	
	Seed Drill, 6m (PTO powered)	0.2	hour/ha	
	Roll, 6m	0.2	hour/ha	
	Sprayer, 24m (PTO powered)	0.1	hour/ha	
	Spreader, 12m (PTO powered)	0.2	hour/ha	
	Combine Harvester (200hp)	0.4	hour/ha	
	Total tractor hours	3.3	hour/ha	
Soil Data	Soil Texture	Medium		Select middle-range types
	Soil Organic Matter	1.72 <SOM<= 5.16		

	Soil Moisture	Moist		
	Soil Drainage	Good		
	Soil pH	5.5 < pH <= 7.3		
	Soil Type	Inceptisol		(USDA 2005)
	Average rainfall	840 mm		1971-2000 average for England (Met Office 2012)
Yield Data				
Yield (Wheat grain @13.5% m.c)		7.7	tonnes/ha	(DEFRA et al. 2010)
Yield (Straw- incorporated)		4	tonnes/ha	(Nix 2011)

Table 4 Results of the MCA for the 10 GHG reporting tools assessed.

Category	Farm Based							Bioenergy Based					
	C-Plan	CFF	Muntons	Cool Farm	CALM	CCalc	**Average**	RSB	Biograce	HGCA	BEAT	RTFO	**Average**
User Friendliness	67 %	78 %	56 %	72%	67 %	78 %	**69%**	61%	56 %	72 %	39 %	61 %	**58%**
Informative	50 %	83 %	17 %	100%	83 %	50 %	**64%**	83%	83 %	67 %	83 %	67 %	**77%**
Transparency	17 %	50 %	17 %	83%	75 %	50 %	**49%**	83%	83 %	42 %	83 %	42 %	**67%**
Comprehensivenes s	20 %	10 %	23 %	90%	60 %	33 %	**39%**	90%	80 %	37 %	40 %	43 %	**58%**

Table 5 Emission factor estimates for fertiliser manufacture across tools

Fertiliser	**Emission Factor per kg Nutrient (kg CO_2 eq./kg)**											
Tool	**C-Plan**	**CFF**	**Muntons**	**Cool Farm**	**CALM**	**CCalc**	**RSB**	**RSB (RED)**	**Biograce**	**HGCA**	**BEAT**	**RTFO**
Reference cited	None	No specific referen ce	None	EFMA 2006	No specific reference	North Energy Associates 2006	Ecoinvent	Biograce	(EUCAR et al. 2006)	HGCA	North Energy Associates 2006	No specific reference
'N Fertiliser'	0.63[ac]	-	9.21[bc]	-	-	6.98	-		5.88	6.69	6.92	5.92

Ammonium Nitrate (N)	-	-	-	6.20	3.80	-	8.55	8.16	-	-	-	-
Urea (N)	-	-	-	1.48	1.24	-	3.30	3.07	-	-	-	-
Phosphorous (P_2O_5)	-	-	2.2[c]	1.3	-	1.86	2.02	1.73	1	0.71	1.85	1.01
Potassium (K_2O)	-	-	0.5[c]	1.5	-	1.77	1.44	1.12	0.6	0.46	1.76	0.58

a) This is per kg of fertiliser.
b) Includes N_2O emissions from soil.

This is deduced rather than stated in the tool or supporting manual

Supplementary Material

Table 1 System Boundaries of GHG accounting tools

	Farm-Based Tools						Bioenergy-Based Tools					
Tool	C-Plan	CCaLC	CFF	CALM	Cool	Munt ons	HGCA	Biograce	BEAT	RTFO	RSB (RSB)	RSB (RED)
Wheat Yield	1	0	1	1	1	1	1	1	1	1	1	1
Diesel Consumed	1	1	1	1	1	1	1	1	1	1	1	1
Fertiliser N_2O (total figure)	0	0	0	1	1	0	1	1	1	1	1	1
Fertiliser manufacture	1	1	0	1	1	1	1	1	1	1	1	1
N_2O emissions from residues (ploughed in)	1	0	1	1	1	0	0	1	1	0	1	1
Manure N_2O (direct and indirect)	0	0	0	1	1	0	0	1	0	0	1	1

Seeds	0	1	0	0	0	1	1	1	1	0	1	1
Farm machinery	0	0	1	0	0	0	0	0	1	0	0	0
Pesticides	0	1	0	0	1	1	1	1	1	1	1	1
Purchased Electricity (on farm)	1	1	1	1	1	0	1	0	1	1	0	0
Manure delivery	0	1	1	0	0	0	0	0	1	0	1	0
Transport	0	1	1	0	1	0	1	1	1	1	1	0
Final Distribution	0	1	1	0	1	0	1	1	1	1	0	0
Land use change	0	1	1	1	1	0	0	1	0	1	1	1
Straw Yield	0	0	1	0	1	0	1	0	1	0	1	1
Sequestration in farm features	1	0	1	1	1	0	0	0	0	0	0	0
Lime	0	1	0	1	1	0	1	0	0	0	0	0
Buildings	0	0	1	0	0	0	0	0	0	0	1	0

Table 2 Results of the multi criteria analysis of the GHG accounting tools

Criteria	Score				Tool									
User Friendliness	**3**	**2**	**1**	**0**	**C-Plan**	**CFF**	**Munton**	**CCalc**	**e**	**HGCA**	**Cool Farm Tool**	**CALM**	**BEAT**	**RTFO**
Is the tool readily available?	Yes- online or ready to download	Yes - but requires installation	Yes- but requires permission /password	Not available	3	3	1	3	3	3	3	3	2	2
Is support available?	Yes- A support telephone number	Yes - A support email addres	Less Obvious	None	2	2	2	3	2	1	0	1	0	2
Are manuals provided?	Yes - Detailed with data collection guideance	Yes - detailed manual	Basic instructions	None	0	3	1	2	2	2	3	3	2	2
Target User	Any	Some knowledge required	Trained user	Expe rt	3	3	3	2	2	3	2	3	2	2
Quality of Tool design and architecture	Very easy to use	Some navigation required	Limited but functional	Not user friendly	3	2	3	2	1	3	2	2	1	1
Are alternative units are provided?	Yes - to many inputs	Yes - to some	A few key inputs	No	1	1	0	2	0	1	3	0	0	2
Rating					***67%***	***78%***	***56%***	***78%***	***56%***	***72%***	***72%***	***67%***	***39%***	***61%***
Informative														
What format are results provided in?	Graphical and tabular	Tablular	A single number and a graph	A single number	2	2	1	3	2	3	3	2	3	2

Does the tool provide a breakdown of where emissions occur?	Yes - clear demonstration of where results occur	Emissions are grouped into categories but separate emissions can be calculated	Emissions are grouped into categories	No breakdown	1	3	0	0	3	1	3	3	2	2
Rating					***50%***	***83%***	***17%***	***50%***	***83%***	***67%***	***100%***	***83%***	***83%***	***67%***
Transparency														
Upfront level of transparency of emission factor data	Full & detailed disclosure of data	Limited disclosure of data	Can be estimated by manipulation of input data	No details given	0	2	0	3	1	1	2	1	3	3
Is it clear whether or not direct and indirect emissions are included for N2O emissions?	They are measured separately/this is stated in the supporting material	From the resources used it is clear whether or not this is included	Not referenced, but from the results it is clear whether this is included	Not evident	0	0	1	2	3	1	3	3	1	1
Is it clear whether emissions from crop residue incorporation are included?	They are measured separately/this is stated in the supporting material	From the resources used it is clear whether or not this is included	Not referenced, but from the results it is clear whether or not this is included	Not evident	1	3	0	0	3	2	3	3	3	0
Are global warming potentials stated?	Yes GWP's are stated and referenced	Separate GHG's are listed but as CO2 equivalents	All results are provided as CO2 equivalents.	CO2 only given	1	1	1	1	3	1	2	2	3	1
Rating					***17%***	***50%***	***17%***	***50%***	***83%***	***42%***	***83%***	***75%***	***83%***	***42%***
Comprehensiveness: Major Impacts														
Does the tool include emissions from fertiliser application?	N, P and K are included separately	Only N is included	Fertilisers' are grouped into one category	Not included	1	0	3	3	3	3	3	2	3	3
Does the tool differentiate between N fertiliser types?	Yes a few types of N fertiliser	Yes- between organic and non-organic	N fertiliser is only measured as 'kg N'	No/Not included	0	0	2	1	1	2	3	3	2	1
Does the tool include emissions from fertiliser manufacture?	Yes - with references provided for specific fertiliser	Yes but for generic 'N fertiliser' emission factor	Yes but not referenced	Not clear/no	1	0	1	2	1	2	3	1	2	2

Does the tool include direct N2O emissions from fertiliser application?	IPCC - higher tier applied	IPCC Tier 1	Another method used	Not clear/no	1	0	2	0	3	2	3	2	2	2
Does the tool include indirect N2O emissions from fertiliser?	IPCC - higher tier applied	IPCC Tier 1	Another method used	Not clear/no	1	0	0	0	3	2	3	2	0	2
Are soil parametres required for N2O emissions?	Yes - the N2O results depend on it	Can be otherwise defaults are used	Yes but is not apparently used	Not clear/no	0	0	0	0	2	0	3	0	0	0
Does the tool include N2O emissions from crop residue incorporation?	IPCC method used and results are based the defined fate of straw	IPCC - but not linked to any information specified by user	Some other method	Not clear/no	1	1	0	0	3	0	3	2	2	0
Does the tool include N2O emissions from manure application?	IPCC - higher tier applied	IPCC Tier 1	Another method used	Not clear/no	0	0	0	0	3	0	3	3	0	0
Is uncertainty addressed?	Yes- for inputs and emission factors including N2O emissions	N2O emissions uncertainty included	Uncertainty in inputs and emission factors included	No uncertainty addressed	0	0	0	1	2	0	0	0	1	0
Does the tool include land use change?	Yes - from specific land conversion scenarios - with references	Yes- from specific changes in soil SOC	Yes in some way but it is not referenced	Not included	1	2	0	3	3	0	3	3	0	3
Rating					***20%***	***10%***	***27%***	***33%***	***80%***	***37%***	***90%***	***60%***	***40%***	***43%***

Comprehensiveness: Minor Impacts

Table 3 List of Excluded Tools

Producer	Tool	Access	Brief Description	Website
Excluded: Not available in the public domain for free				
Carbon Trust	Carbon Trust Footprint Expert	Purchased	Carbon footprint tool for products	http://www.carbontrust.com/client-services/footprinting/measurement
Centre of Excellence of UK Farming	CEUKF wheat GHG assessment tool	Used in-house		http://www.ceukf.org/sustainability-and-sustainability-indices/
Scottish Agricultural College	SAC	Used in-house		http://www.sac.ac.uk
SEE 360 Ltd	C-PLANv2	Purchased	Farm-based carbon reporting	http://www2.cplan.org.uk
Excluded: UK focus but too specific				
Rothamstead Research	RothC	Download programme	Process-based model for the turnover of organic carbon	http://www.rothamsted.ac.uk/aen/carbon/rothc.htm
Excluded: Non-UK specific				

EUFEX	Eufex GHG Calculator	Online	GHG calculator for crop production	http://eufex.eu/GHG%20Calculator
Leiden University	CML Greenhouse Gas Calculator for Electricity and Heat from Biomass	Download spread sheet	GHG calculator for bio-electricity and heat	http://www.cml.leiden.edu/research/industrialecology/researchprojects/projects/co2-calculator.html
Victoria Government	Greenhouse in Agriculture	Download spread sheet	Greenhouse gas accounting of grain production in Australia	http://www.greenhouse.unimelb.edu.au
Winemakers Fed. Of Australia	International Wine Carbon Calculator	Download spread sheet	Carbon calculator for wine in Australia	http://www.wfa.org.au/entwineaustralia/carbon_calculator.aspx
United States Department of Agriculturel	COMET-VR	Online	Examines the annual carbon flux of soils in the US using a dynamic Century model simulation.	http://www.cometvr.colostate.edu
Queensland University of Technology	Farming Enterprise GHG Calculator	Online	GHG calculator of farm-based emissions in Queensland, Australia	http://www.isr.qut.edu.au
Lincoln University	Lincoln Farm Carbon Calculator	Online	GHG calculator for farming activities in New Zealand	http://www2.lincoln.ac.nz/carboncalculator/

	Australian Farm GAS Calculator	Online	Tool to investigate how effect of management on GHG emissions on a farm in Australia.	http://afi-calc-dev.sitbacksolutions.com.au/login
Agriculture and Agri-Food Canada	HOLOS	Download programme	A whole-farm modelling software program that estimates greenhouse gas (GHG) emissions based on individual farms.	http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1226606460726&lang=eng
Food and Agriculture Organisation of the United Nations	FAO EX-ACT (EX-ante Appraisal Carbon Balance Tool)	Download spread sheet	Tool to examine the impact of agriculture and forestry development projects on GHG emissions and carbon sequestration.	http://www.fao.org/tc/exact/ex-act-tool/en/
University of New Hampshire	DeNitrification-DeComposition	Download programme	Process-based model for examining N2O fluxes from soils	http://www.dndc.sr.unh.edu
Texas A&M AgriLife Blackland Research and Extension Center	APEX - Agricultural Policy Environmental eXtender	Download programme	Process-based model for examining whole farm/small watershed management.	http://apex.tamu.edu/
NASA	NASA-CASA CQUEST	Download programme	Process-based model examining carbon sequestration predictions of soil.	http://geo.arc.nasa.gov/sge/casa/cquestwebsite/index.html

Colorado State University	DAYCENT/ CENTURY	Download programme	Simulates fluxes of C and N among the atmosphere, vegetation, and soil	http://www.nrel.colostate.edu/projects/daycent/downloads.html