# Carbon accounting tools: are they fit for purpose in the context of arable cropping?

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## Abstract

The agricultural sector contributes 9% towards total UK greenhouse gas emissions and so may offer significant potential as a sector to help meet national and international emission reduction targets. In order to help farmers manage their emissions and to encourage more sustainable farming several carbon accounting tools are now available. This paper describes a short study that selected five suitable tools and compared their performance on nine European arable farms, concentrating on the crop production components, to determine how useful they are for assisting in the development of site specific mitigation strategies and how well they would perform within farm assurance or benchmarking schemes. The results were mixed, with some tools better designed for identifying mitigation opportunities than others. The results also showed that, quantitatively, the results are highly variable between tools and depended on the selected functional unit, this being highly important if the wider aspects of sustainability such as food security are to be considered. However, there is statistical consistency across the tools regarding the ranking order of the farms in terms of their emissions.

**Keywords:** agriculture; climate change; greenhouse gas emissions; carbon accounting



## Introduction

The change in atmospheric concentrations of greenhouse gases (GHGs) due to anthropogenic emissions, and the impacts on climate are issues that have risen up the political and societal agenda in recent decades. The consequences of climate change are potentially severe and may include significant detrimental impacts on human health, crop production, ecosystems and biodiversity (e.g. Araújo *et al*., 2011; Lobell *et al*., 2011; McMichael & Lindgren, 2011; Rosenzweig *et al*., 2008). Climate change, coincidental with a rapidly increasing population, also has implications for food security (IAASTD, 2008). Actions should therefore be taken to reduce GHG emissions as part of broader efforts to encourage sustainable development (Aitken *et al*., 2011; Kennedy, 2011; Defra, 2010, Stern, 2006).

In 2005, the Kyoto Protocol came into force which recognised the need to reduce emissions globally. This international agreement sets binding targets for developed nations to reduce their GHG emissions to an average of 5% below the 1990 level. For the European Union (EU-15 at that time) the actual target was 8% below the 1990 level for the period 2008-2012. However, the EU-27 has been more ambitious and has established a unilateral emissions reduction target of 20% by 2020 (European Commission, 2007). Some Member States have set even more challenging targets. For example, in the United Kingdom, under the Climate Change Act, 2008, a legally binding target of at least an 80% reduction in emissions by 2050 has been set and Germany has a national target of a 40% reduction by 2020 (European Commission, 2011). As the Kyoto Protocol's main provisions expire in 2012, a second round of emissions abatement under the existing agreement have been approved whilst a new global agreement is negotiated for implementation by 2020.

The agricultural sector contributes 9% towards total UK GHG emissions (AEA, 2011), 9% in Europe (European Commission, 2009) and about a third of emissions globally (Harvey & Pilgrim, 2010; Solomon *et al*., 2007). The sources are varied and include carbon dioxide emissions from fossil fuels, electricity and losses from disturbed soils, methane from livestock enteric fermentation and the handling of organic wastes, and nitrous oxide from the use of fertilisers and manures (Flynn & Smith, 2010; Paustian *et al*., 2004). Agricultural activities can also significantly enhance the sequestering of carbon dioxide in the soil or in vegetation thus reducing net emissions. It has been estimated that opportunities for mitigating these emissions could be substantial, subject to overcoming various economic and other constraints (Hillier *et al*., 2011; Smith *et al.*, 2008). Consequently, if emission reduction targets are to be met then agriculture must play its part and each farm should be encouraged to adopt sustainable, climate friendly farming techniques that help minimise the emission of greenhouse gases and maximise carbon sequestration. This could be done by raising farmer awareness of the sources, management and mitigation of emissions and there is plenty of generic advice available (e.g. ADAS, ud; AHDB, 2009). However, every farm is unique in the enterprises it undertakes, the farming approach adopted and the local environmental conditions, all of which affect the quantities of GHGs emitted. Ideally, each farm needs to be assessed individually and farm specific mitigation plans developed. It is very difficult to manage what cannot be measured and, consequently, a number of carbon accounting tools have been developed for farmers to assess their GHG emissions (e.g. Hillier *et al*., 2011; T*zilivakis et al*., 2010).

Carbon accounting, also known as carbon footprinting, is not new and its history is associated with Life Cycle Assessment (LCA). The approach estimates the amount of GHG emissions (which includes carbon dioxide, methane and nitrous oxide) produced during a defined time period (which is often a products lifecycle or, for farming, a production season or rotation), expressed in carbon dioxide equivalents ($CO_2e$) – a measure used to compare the emissions of various greenhouse gases based upon their global warming potential (Smith *et al*., 2007; 2008). Within LCA the net $CO_2$e (the total emissions minus that sequestered or offset) can then be used to estimate Global Warming Potential - an LCA impact category. Due to increasing use of this indicator, and the need to compare values across organisations and processes, two standards are now publically available (PAS2050 (BSI, 2008) and the GHG Protocol Product Standard (WRI, 2011)) that seek to provide transparent and robust frameworks to estimate GHG emissions. Both standards are broadly similar and categorise emissions sources into 3 Scopes. For farming, Scope 1 emissions are those directly in the control of the farmer such as those from on-farm fuel use and fertiliser applications. Scope 2 refers to indirect emissions arising from electricity. Scope 3 emissions are those from indirect sources such as those from the manufacturer of inputs such as fertilisers and pesticides and are an optional reporting requirement within both standards.

In their simplest role these techniques can be used to raise awareness and to educate. However, just knowing the quantity of emissions is not particularly valuable unless action is taken to reduce them and so carbon accounting tools also have a role facilitating informed management and purchasing decisions and for the development of site specific mitigation plans. The use of such tools within primary production assurance schemes is also gradually being introduced. For example, farmers who are members of Conservation Grade, a UK assurance scheme for cereal farmers must use carbon accounting methods (Conservation Grade, 2012) and other schemes are following suit (Franks & Haddingham, 2011). In addition, the European Commission is currently considering the potential of introducing a low carbon farming scheme in the European Union centred around a carbon accounting approach coupled with a benchmarking system (European Parliament, 2010). In recent years benchmarking has become a popular way for policy makers to stimulate the uptake of agricultural best practice (Policy Commission, 2002; Ashworth, 2002). The technique enables individual farmers to compare their own performance against others or against an agreed standard and, by doing so, they are encourage to adopt more sustainable practices (Hagemann *et al*., 2011). Therefore, if a carbon accounting tool is to be useful it must be reliable, credible and be able to identify where a pragmatic change in farm practices can lead to a cost-effective reduction in emissions. Thus, it must be capable of coping with the wide variety of site and business specific properties which can influence the quantities of GHGs lost (Hillier *et al*., 2011; Del Grosso *et al*., 2006). Whilst it may be assumed that carbon accounting tools that use a standard approach would produce similar results, this is not always the case for reasons of boundary setting, scope and the variability in emission factors used (Padgett *et al*., 2007; Kenny & Gray, 2008; Röös *et al*., 2010). This, therefore, raises the question of how comparable these tools actually are and whether or not any differences affects their fitness for purpose.

This paper presents the findings of a study that compared a number of carbon accounting tools available to European arable farm businesses, the aim being to compare their performance, to evaluate their ability to guide farmers to adopt more climate friendly practices and to question their value within benchmarking and assurance schemes.

## Methods

The study had three main stages. The first was concerned with tool selection and their characterisation. Secondly, data was collected from farms and finally a comparison exercise was undertaken whereby the GHG emissions for each farm were determined using each of the selected tools and the data generated compared to (i) identify and explain any differences in the results generated by each tool for each of the case study farms, particularly for any implications for deciding mitigation options and (ii) to compare the results from the nine farms and to identify if mitigation options likely to be adopted would be different depending upon the tool selected.

### Tool selection and characterisation

Carbon calculator tools suitable for use in European agriculture and publically available free-of-charge were sought for use in this study. Several tools were identified but excluded as their field of application was not considered applicable to traditional European agriculture (e.g. CFF, 2010; McPhee *et al.*, 2010; NRCS, 2007), because they were still in the development stage (Solagro, 2012) or, as is the case with certain versions of CPLAN (CPLAN, 2012), attract a user licence fee. Nevertheless five suitable tools were identified: CALM (CLA, 2012), CCalC (CCALC, 2011), COOL (Hillier *et al.*, 2011) CPLANv0 (CPLAN, 2012) and IMPACCT (Tzilivakis *et al.*, 2010).

Carbon calculators like many other types of software tools tend to be developed for a specific purpose and/or end user and this can significantly influence the complexity, functionality and user support provided. Fair comparison of their performance against a specific requirement needs to take these design parameters into consideration. In order to facilitate this, each of the tools was characterised against a number of criteria considered important if the tool was to be used by farmers to encourage GHG mitigation.

### Standard scenarios

Nine case study farms were identified across Europe via research networks and personal contacts using purposive sampling to rapidly identify a targeted sample of farms that were growing similar crops, broadly representative of European production and were implementing good farming practice. For each farm, data was collated during 2009/10 regarding their types of operation, site specific details, productivity and quantities of inputs (e.g. inorganic and organic fertilisers, pesticides, energy and fuel use, water user etc.). The scenarios only include details of production and so the carbon balances are on a 'production only basis' and do not consider emissions and sequestration related to the non-productive areas of the farm (e.g. margins, hedgerows etc.) nor to aspects such as transport. All of the tools, with the exception of CCalC, include the estimation of carbon sequestration, however, approaches are very different across the tools and so results can be highly variable and uncertain (Smith *et al*., 2007). Therefore, whilst accepted that these areas of a farm are highly valuable for meeting national and international emission reduction targets, this aspect has not been included in the study and all comparisons are done on the basis of gross GHG emissions only. The information gathered is summarised in Table 1.

**Table 1: Summary of case study farms**

| | Area of crop ha | Annual yield tonnes | Inorganic fertiliser as tonnes N | Organic fertiliser tonnes | Pesticide inputs kg active substance H/I/F[1] | Diesel use litres |
|---|---|---|---|---|---|---|
| **CS1: Germany**: 1025ha, loamy sand soils, 510mm mean annual rainfall, 8.7°C mean annual temp. Crops harrowed, ploughing depth 25cm. Pesticides applied by broadcast sprayer. No irrigation, lime or nitrification inhibitors. Residues removed. | | | | | | |
| OSR | 295 | 1180 | 88 | 1475 PL[2] | 117/59/59 | |
| Barley | 183 | 1375 | 45 | 450 PL[2] | 137/19/129 | |
| Rye | 163 | 1060 | 45 | - | 120/0/85 | 43930 |
| Triticale | 150 | 1000 | 31 | 375 PL[2] | 112/15/105 | |
| W. wheat | 227 | 1700 | 80 | - | 170/38/23 | |
| **CS2: Hungary**: 5ha, deep fertile loam soil, 650mm mean annual rainfall, 10°C mean annual temp. Ploughing depth 20cm. Pesticides applied by broadcast sprayer. No irrigation, lime or nitrification inhibitors. Residues removed. | | | | | | |
| Wheat | 1.0 | 6.0 | 0.2 | - | 0.001/0.002/0.001 | 49 |
| Maize | 0.5 | 4.5 | 0.035 | - | 0.001/0/0 | |
| **CS3: Hungary**: 37ha, light sand soil, 650mm mean annual rainfall, 9.4°C mean annual temp. Ploughing depth 20cm. Pesticides applied by broadcast sprayer. No irrigation, lime or nitrification inhibitors. Straw incorporated. | | | | | | |
| Wheat | 8.0 | 40 | 0.7 | - | 0.01/0.01/0.01 | |
| Barley | 5.0 | 20 | 0.5 | - | 0.01/0.01/0.01 | 575 |
| OSR | 5.0 | 10 | 0.7 | - | 0.01/0.01/0.01 | |
| **CS4: Hungary**: 2100ha, fertile loam soil, 650mm mean annual rainfall, 9.8°C mean annual temp. Ploughing depth 20cm. Pesticides applied by broadcast sprayer. No irrigation, lime or nitrification inhibitors. Straw incorporated. | | | | | | |
| Maize | 1289 | 9000 | 230 | - | 20.0/0/10.0 | |
| Wheat | 630 | 3465 | 130 | - | 10.0/10.0/10.0 | 45260 |
| OSR | 73.2 | 250 | 9.0 | - | 10.0/10.0/10.0 | |
| **CS5: Hungary**: 31ha, sandy loam soil, 575mm mean annual rainfall, 9.2°C mean annual temp. Ploughing depth 15cm. Pesticides applied by broadcast sprayer. Mo irrigation or nitrification inhibitors. Straw incorporated. | | | | | | |
| Wheat | 10.0 | 55.0 | 1.0 | - | 0.01/0.01/0.01 | 764 |
| OSR | 11.5 | 29.0 | 1.5 | - | 0.01/0.01/0.01 | |
| **CS6: Poland**: 160ha, medium loam soils, 580mm mean annual rainfall, 8.4°C mean annual temp. Ploughing depth 20cm. Pesticides applied by broadcast sprayer. Potatoes are irrigated. No nitrification inhibitors. Straw incorporated. OSR dried on site. | | | | | | |
| Wheat | 55 | 330 | 8.3 | - | 100/75/100 | |
| Barley | 40 | 300 | 3.2 | - | 50/50/60 | 6453 |
| OSR | 20 | 70 | 3.6 | - | 50/50/40 | |
| Potatoes | 10 | 400 | 1.3 | - | 50/50/0 | |

| | Area of crop ha | Annual yield tonnes | Inorganic fertiliser as tonnes N | Organic fertiliser tonnes | Pesticide inputs kg active substance H/I/F[1] | Diesel use litres |
|---|---|---|---|---|---|---|
| **CS7: Poland**: 70ha, medium-heavy soils, 580mm mean annual rainfall, 8.5°C mean annual temp. Ploughing depth 25cm. Pesticides applied by broadcast sprayer. No irrigation or nitrification inhibitors. Straw incorporated. | | | | | | |
| Wheat | 30 | 180 | 4.0 | - | 3.0/3.0/3.0 | 4266 |
| OSR | 20 | 60 | 3.0 | - | 2.0/2.0/2.0 | |
| **CS8: Poland**: 250ha, medium to heavy loam soils, 590mm mean annual rainfall, 8.4°C mean annual temp. Ploughing depth 25cm. Pesticides applied by broadcast sprayer. Potatoes irrigated. No nitrification inhibitors. Straw incorporated, wheat – discing, rolling, potatoes – sub-soiling, ridging. | | | | | | |
| Wheat | 125 | 750 | 21.9 | - | 20/20/20 | 18850 |
| OSR | 50 | 150 | 7.5 | - | 20/50/20 | |
| Potatoes | 10 | 400 | 2.0 | - | 6/6/0 | |
| **CS9: England**: 490ha, medium loam soil, 640mm mean annual rainfall, 8.8°C mean annual temp. Ploughing depth 20cm. Pesticides applied by broadcast sprayer. No irrigation, lime or nitrification inhibitors. Straw incorporated. | | | | | | |
| W. wheat | 180 | 1530 | 39.5 | - | 320/4/140 | 22968 |
| S. barley | 153 | 873 | 23.0 | - | 38/0/40 | |
| OSR | 117 | 351 | 20.3 | - | 350/40/75 | |

**Key:** [1] H/I/F – Herbicides/Insecticides/Fungicides; [2] PL – Poultry litter



## Results

### Characterisation of the calculators

If a tool is to be used by farmers, without formal training, as is the expected approach for most freely available software tools, it must be easy to use, intuitive and functional as well as credible and intelligible (Gelb & Offer, 2005). The two online systems CPLANv0 and CALM are undoubtedly the easiest to use and require the least input data. IMPACCT is the only bespoke, standalone software package designed for installation on a computer and so is the most sophisticated regarding presentation and user functionality. COOL and CCalC are spreadsheet based applications and are restricted by the inherent design limitations of the spreadsheet software itself and rely on the end user reporting facilities provided by the spreadsheet package. All tools provide some degree of user help either on screen, within separate documents or in the case of IMPACCT as integral video. All tools were found to be reasonably simple to use and should not deter farmers from using them although the spreadsheet systems were borderline in this respect. The websites of all tools describe the broad methodological approach adopted but, with the exception of IMPACCT, documentation detailing the calculations is limited. Perhaps more importantly, identification and so traceability of the emission factors used is not available in any of the tools other than for IMPACCT. The findings of the broader characterisation process have been summarised in Table 2.

**Table 2: Tool characterisation**

| | IMPACCT | CALM | CPLANv0 | COOL | CCalC |
|---|---|---|---|---|---|
| **OBJECTIVES** | | | | | |
| **Targeted end** | European | UK based farm | UK based farm | Global farmers, | UK Supply chain |

| | | | | | |
|---|---|---|---|---|---|
| **user** | farmers, land managers, policy makers. | and land managers. | and land managers, policy makers. | supply chain managers and companies. | managers, policy makers, env. officers. |
| **Aim** | Identification of mitigation & efficiency options at farm or regional level. | Identification of options to cut emissions & increase efficiency. | Management tool for assessing & monitoring GHGs and to inform policy. | Identification of options to cut emissions & increase efficiency. | Supply chain optimisation & monitoring, LCA studies, basic assessments. |
| **GENERAL APPROACH** | | | | | |
| **Methodology / Scopes** | IPPC 2010 and PAS2050 compliant. Scope 1, 2 & 3 | IPPC 2006, 2009 UK Nat. Inventory. Scope 1, 2 & 3 | IPPC 2006. PAS2050 compliant. Scope 1 & 2 | IPPC 2010. Scope 1, 2 & 3 | IPPC and PAS2050 compliant. Scope 1 & 2 |
| **Depth/detail** | Comprehensive | Moderate | Very basic | Comprehensive | Comprehensive |
| **Functional unit** | Whole farm, per tonne, per product | Whole farm | Whole farm | Whole farm, per hectare, product & tonne | User defined |
| **Output as** | Tonnes $CO_2$e | Tonnes $CO_2$e | Tonnes Ce | Tonnes $CO_2$e | Tonnes $CO_2$e |
| **Sequestration** | Included | Included | Included | Included | Omitted |
| **DATA AND TIME REQUIREMENTS** | | | | | |
| **Data needs** | High | Moderate | Low | High | High |
| **Data availability** | High | High | High | Moderate | High |
| **USER FRIENDLINESS** | | | | | |
| **Output design, reporting & data storage facilities** | Various options, tabulated & customised reports. Data saving routines. | Multiple options inc. tabulated results summarised. Stored online. | On screen summary only, no reporting or data storage options. | Standard Excel options & facilities. Stored as Excel spreadsheets | Standard Excel options & facilities. Stored as Excel spreadsheets |
| **MANAGEMENT** | | | | | |
| **Status** | Free pilot version. Bespoke software. | Free. Web based input. | Basic version free, advanced pay-to-use. Web based. | Free. Spread sheet based tool. | Free. Spread sheet based tool. |
| **User support** | Telephone helpline & email | Email | Email | None | Telephone helpline & email |
| **Updated?** | As required | Yes | Yes | No data | No data |
| **Website address** | www.herts.ac.uk /aeru/impacct/ | www.calm.cla. org.uk/ | www2.cplan.org. uk/ | www.unilever. com/ | www.ccalc.org.u k/ |
| **Developers /owners** | University Herts/ European Commission | Country Land and Business Association | Independent - Scottish farmers | Unilever | Manchester University |



The categorisation process is useful as it highlights that whilst the tools have the same broad objective, i.e. calculating a farms carbon balance, there are significant differences between them. IMPACCT and COOL were designed specifically for identifying mitigation opportunities and the carbon balance is a consequence of this process rather than its primary objective. Both these tools also consider costs and offer information on other types of environmental impacts that may occur. CCalC has a supply chain focus with the main objective of optimising the supply chain as a whole rather than a specific process (e.g. the farm) within it. For CALM and CPLANv0, the main objective is to calculate the farms carbon balance in order to inform and raise awareness.

There are, however, consequences of the different objectives. CALM, CPLANv0 and CCalC require minimal data inputs and data is entered as farm totals (unless the end user has data for each activity or product and explores these individually). Whilst minimal data input may be desirable from the end users perspective it inevitably means more assumptions are made during the calculation. For example, the simplest of the five tools, CPLANv0, requires the quantity of fertiliser product applied to be input. Fertiliser type is not declared and assumptions are therefore made as to its nitrogen content. However, the latter varies significantly from one manufactured fertiliser to another. For example ammonium nitrate usually contains 34.5% N were as Urea contains around 46% N. The other tools either require the total nitrogen to be input or the total quantity of product plus the percentage nitrogen within it. Minimal data inputs will also limit the amount of the decision support that can be provided for identifying mitigation opportunities, as it allows few opportunities for varying the inputs to see how the carbon balance is affected.

IMPACCT, the most detailed of the five tools examined, requires data related to actual farm practices (e.g. individual cultivations, machinery maintenance, use of driver aids for fuel efficiency) such that these can be compared to best practice or examined for mitigation potential. COOL, operates best on a product basis (e.g. wheat, barley, dairy) and requires data specific to that product and, for fuel use, provides the user with a choice of either whole farm or by individual activity (e.g. sowing, tillage). It is also more detailed regarding farming practices than the simpler tools.

Whilst all the tools can identify the main emission sources only IMPACCT and COOL are sufficiently detailed to help identify what can actually be done about it. For example, all tools can show that reducing fuel use will provide a modest reduction in emissions. CALM, CPLANv0 and CCalc leave it to the farmer to identify how such a reduction in fuel consumption can be best achieved. COOL, by exploring what-if scenarios and repeatedly re-running the software, allows mitigation plans to be developed. Whereas, IMPACCT identifies all mitigation options automatically and ranks these according to the percentage $CO_2$e savings possible.

There are also differences between the tools regarding what is included within the calculations. For example, CPLAN and CCalC do not include Scope 3 emissions, whilst the other calculators either included them automatically or offer inclusion as an option. Scope 3 emissions vary with product and selecting those with lower emissions is a potential mitigation opportunity. For example, the production of urea, an important straight nitrogen fertiliser, generates significantly lower GHG emissions that that of calcium ammonium nitrate (EFMA, 2009). The inclusion of Scope 3 emissions also has wider implications by acting as a driver for cleaner production.

There are also differences regarding how emissions and sequestration relating to crop residue management is handled. IMPACCT and CCalC do not report these sources separately. CPLANv0 makes general assumptions regarding residue management and reports net emissions, CALM provides the user with a limited option of declaring if residues are exported from farm or not and again net emissions are reported. COOL provides a number of options of how residues may be managed including their export from farm, soil incorporation, composting or field heaps.

One potential consequence of these differences is that the results could place greater or lesser emphasis on a particular emission source and thus different calculators could drive mitigation plans in different directions. Differing plans may not necessarily be wrong but they may not be cost-benefit optimised.

**Comparison of the tools**

The results provided by the five tools for each of the case study farms are shown, on a per hectare basis, in Figure 1. The average gross GHG emissions calculated from the nine farms is 2.3 t $CO_2$e $ha^{-1}$. This is lower than that derived by the UK Carbon Baseline Survey (Natural England, 2008) of 3.2 t $CO_2$e $ha^1$, a relatively small difference compared with the general variation across the tools. However the Natural England study is very different to that described herein as it looked at 200 farms of variable type (not just arable) and all were UK based. In addition, the Natural England study only used the CALM tool which is shown herein to report higher than the other tools.

Table 3 shows the differences between the results as their Standard Deviations (s.d.) for each case study farm across the five tools.

**Table 3: Results as the Standard Deviation**

| | **CS1** | **CS2** | **CS3** | **CS4** | **CS5** | **CS6** | **CS7** | **CS8** | **CS9** |
|---|---|---|---|---|---|---|---|---|---|
| **Data range* Total gross $CO_2$e $ha^{-1}$** | 1.88-5.01 | 1.00-1.93 | 0.64-1.17 | 0.91-2.17 | 0.80-1.57 | 0.94-1.94 | 0.99-2.03 | 1.17-2.38 | 1.05-2.46 |
| **Std Deviation** | 1.279 | 0.397 | 0.362 | 0.475 | 0.313 | 0.428 | 0.402 | 0.459 | 0.542 |
| **Variance** | 1.637 | 0.157 | 0.131 | 0.225 | 0.098 | 0.183 | 0.162 | 0.201 | 0.235 |

* Excluding Scope 3

A number of trends from the data in Figure 1 can be observed. The emissions for fuel use are very similar across all tools (s.d. ranges 0.006-0.019 across the nine farms) implying that similar emission factors are being used.

For the other emission categories there are significant differences in the results provided by the five tools. As expected the bulk of the GHG emissions come from fertiliser use. However examining the variance across each case study the difference between the tool reporting the highest value and that reporting the lowest is as great as 240% (CS2, $CO_2$e range from 0.43 (COOL) to 1.47 (CALM) tonnes $ha^{-1}$). The s.d. ranges from 0.175-0.738 across the nine farms. It can also be noted from Figure 1 that for GHG emissions resulting from fertiliser applications CALM is consistently higher than the other tools whereas COOL is significantly and consistently lower.

Scope 3 emissions also vary considerably. The variance between the tool reporting the highest value and that reporting the lowest is around 95% (CS5, $CO_2$e range from 0.44 (CALM) to 0.86 (COOL) tonnes $ha^{-1}$). For this aspect CALM is consistently lower than COOL and IMPACCT, the latter two tools giving very similar results. In this case the s.d. ranges from 0.150-0.393 across the nine farms. Note Scope 3 emissions have been excluded from the totals displayed in Figure 1.

One interesting observation which has implications for mitigation planning is that for IMPACCT and CALM the GHG emissions for fertiliser applications on these particular farms are usually higher (depending upon the environmental conditions) than the associated fertiliser manufacturer emissions. For COOL that relationship is reversed and Scope 3 emissions are higher than those for fertiliser application. Therefore, users relying on the COOL tool may not, when considering the cost-benefits of various mitigation options, come to the same conclusions as they would if using a different tool.

**Relative comparison of the case study farms**

Another approach that can be used to compare the tools is to consider how they rank the nine farms for GHG emissions. One issue for these types of comparison studies is the choice of functional unit (FU) and this needs careful consideration as often the study outcomes will differ depending on that choice (Audsley *et al*., 2009; Haas *et al*., 2000, Van der Werf *et al*., 2007). To ensure a sustainability perspective this study used three different FUs. Firstly, a FU of '1 hectare of land' was used as this reflects the lands function of both a producer of food and wider eco-system services as well as being a measure of land management activities. This FU is a common approach adopted by many LCA type studies (e.g. Meisterling *et al*., 2009; Basset-Mens & Van der Werf, 2005). It also strikes a resonance with the original intention of ecological footprinting which is a measure of human demand on the Earth's ecosystems and reported as a normalised measure of land area called 'global hectares' (gha). Secondly, in order to consider the farms productivity intensity and the wider associated food security issues a comparison has been made using a FU of '1 tonne of produce'. Finally, a comparison has also been done using a FU of '€1m of gross farm income' which is a driver for farm profitability and a reflection of a farms financial status as well as the wider societal value of the crops. The analysis was based on typical EU average cereal prices as of February 2012 (Table 4).

**Table 4: Prices used for the FU based on gross farm income**

| Crop | Wheat | Barley | Oilseed Rape | Maize | Potatoes | Rye and Triticale |
|---|---|---|---|---|---|---|
| **Assumed price € per tonne** | 200 | 185 | 430 | 240 | 120 | 120 |

It should be noted that the five tools vary regarding their approach to the functional unit(s) they use. Only CCalC allows the user complete freedom to define the FU used in the calculation (see Table 2). To use the other tools in this manner the end user must manipulate the data themselves.

The Spearmans-Rank Correlation Test was used to illustrate the level of correlation between the rankings of the nine case study farms (Table 5). Some strong correlations can be noted from this data, although these differ between the three FUs. On a per hectare basis there is a strong correlation, to the 99% significance level, for all the tools except COOL. On a per tonne basis all tools, with the exception of IMPACCT, at least to the 95% significance level, are significantly correlated and IMPACCT correlates significantly only with CALM and CCalC. COOL stands out as having the least agreement with the other tools.

**Table 5: Spearman Rank Correlation ($r_s$) between rankings of the 9 case study farms**

| **Per ha** | **IMPACCT** | **CALM** | **CPLANv0** | **COOL** | **CCALC** |
|---|---|---|---|---|---|
| IMPACCT | 1.000 | | | | |
| CALM | 0.933** | 1.000 | | | |
| CPLANv0 | 0.950** | 0.950** | 1.000 | | |
| COOL | 0.733* | 0.867** | 0.932** | 1.000 | |
| CCALC | 0.950** | 0.983** | 0.933** | 0.883** | 1.000 |
| **Per tonne** | **IMPACCT** | **CALM** | **CPLANv0** | **COOL** | **CCALC** |
| IMPACCT | 1.000 | | | | |
| CALM | 0.700* | 1.000 | | | |
| CPLANv0 | 0.650 | 0.983** | 1.000 | | |
| COOL | 0.533 | 0.933** | 0.967** | 1.000 | |
| CCALC | 0.850** | 0.833** | 0.817** | 0.750* | 1.000 |
| **Per income** | **IMPACCT** | **CALM** | **CPLANv0** | **COOL** | **CCALC** |
| IMPACCT | 1.000 | | | | |
| CALM | 0.900** | 1.000 | | | |
| CPLANv0 | 0.800** | 0.950** | 1.000 | | |
| COOL | 0.433 | 0.650 | 0.733* | 1.000 | |
| CCALC | 0.983** | 0.933** | 0.867** | 0.550 | 1.000 |

* 95% significance; ** 99% significance, data excludes Scope 3, based on gross GHG emissions.

Figure 2(a-c), shows the relative rankings of the case study farms, by FU averaged across the five tools (1-high, 9-low). The vertical data points relate to the relative ranking given by the tools. Figure 3 shows the data for each FU averaged across farms and tools for wheat, barley and oilseed rape to provide some indication as to the variation of GHG emissions between crops.

The greatest agreement in ranking occurs with the ranking extremes i.e. the highest and lowest emitters. With respect for all three FUs CS1 appears to be the highest emitter of GHG's (12.79t average $CO_2e$ $ha^{-1}$). This can be traced back to its relatively high levels of fertiliser inputs, the reasons for which are unclear. For example, around 350 kg N $ha^{-1}$ was applied to its wheat crop compared with applications of 100-220 kg N $ha^{-1}$ for the other case studies and 300 kg N $ha^{-1}$ plus further nitrogen from an application of poultry litter on its oilseed rape compared with applications of 120-180 kg N $ha^{-1}$ for the other case studies.

On the 'per hectare' basis the farms with the lowest GHG emissions are CS3 (1.05t average $CO_2e$ $ha^{-1}$) and CS5 (1.23t average $CO_2e$ $ha^{-1}$). On a 'per tonne' basis the results are different. All tools agree that the lowest emitting farm is CS6 (0.17t average $CO_2e$ $tonne^{-1}$), and CS2 is close by (0.23t average $CO_2e$ $tonne^{-1}$) but has less agreement across tools, CCalC and COOL rank it slightly lower. The same trend is shown, with slightly better agreement across the tools, when viewed on an emissions 'per gross income' basis whereby are CS6 (0.76kg average $CO_2e$ per €1m income) and CS2 (0.79kg average $CO_2e$ €1m income) compared to the highest emitter CS1 (1.68kg average $CO_2e$ per €1m income).

In the middle of the ranking there is far less agreement. For example: CS4 is the third highest emitter, ranked on the average tonnes $ha^{-1}$ basis but its ranking varies from 4 to 8 depending upon which tool is used.

Looking at the data in Figure 2(a-c) in conjunction with the data in Figure 3 other observations can be made. In the case of CS5, all tools agree that on a per hectare and a per gross income basis this farm is one of the lowest emitters. However, on a per tonne basis CS5 is amongst the higher emitters but there is less agreement in the rankings between tools. This shift in ranking according to its FU suggests that whilst the farm has a more extensive system its overall farm yields are low but the crops grown are valuable. More than half of the productive area of CS5 is dedicated to oilseed rape. Figure 3 shows that on a per hectare basis there is not a great deal of difference between the three crops. However, on a per tonne basis oilseed rape is noticeably higher, almost twice as much as that of wheat and barley but is slightly lower per gross income, because of its higher market value.

Similarly, CS7 is a low emitter on a per hectare basis but high when considered per tonne and its ranking falls mid-way on the per gross income basis. CS9 is a high emitter on both the per hectare and the income basis but has a lower ranking on a per tonne basis. Again this can be explained by the lower yields of high value oilseed rape.

## Discussion and conclusions

This study has considered the carbon balances of nine arable farms calculated by five different carbon calculators. There is no doubt that there are considerable differences between the results provided by the five tools when the actual emissions data is examined. Whilst the causes of some differences can be identified easily and attributed to different objectives, approaches and degrees of complexity, the reasons for some differences, particularly related to fertilisers, are less transparent. It is probable that these differences are caused by different emission factors but as most of the tools are not transparent in this respect this cannot be verified. If an end user is loyal to a particular tool and uses it only for self motivation and awareness building then all the tools examined serve this purpose adequately and, it could be argued, that the simpler the tool the better as it will be less demanding to use.

However, difficulties arise when trying to use the tool to develop mitigation strategies. Within arable cropping systems the farmer essentially has three options (i) reduce fuel use (ii) more efficient fertiliser use or (iii) modify crop residue practices or perhaps tillage. If, for example, an arbitrary target of a 10% emissions reduction were to be adopted, for fuel use, even if fuel consumption was cut to the bare minimum a 10% reduction in emissions is unlikely to be achieved. Using the five tools, typically a 50% reduction in diesel consumption produces a reduction of just a few percent in overall farm emissions. For fertiliser applications around a 10% reduction in applied nitrogen could produce a 10-40% reduction in total farm emissions depending on the tool used. In the case of a farm not using best fertiliser practice this may be achievable by, for example, optimising quantities of applied nitrogen or using nitrification inhibitors but where best practice is already in place this may not be impossible without detrimental effects on farm yields which will have consequences for the farms financial viability and food security as well as affecting the carbon balance on a per tonne and per income basis. The same arguments hold for crop residue management. Consequently, for a well managed farm if a net reduction in emissions is to be achieved there are few options for making large single changes to practices. However, the accumulated savings from multiple small changes may become significant and the tools will only, therefore, be useful if they provide sufficient detail for these issues to be explored. IMPACCT does help explicitly in this respect by, for example, showing the reductions that may be achieved by reducing ploughing depth, by better selection of equipment such as drills and harrows or by improving driving efficiency. Individually such changes may only offer the opportunity of saving 1-1.5% reductions in emissions but collectively the reduction may begin to approach the 10% target (depending on the degree of best practice already adopted on the farm).

When considering the farm comparison data, as with any farm comparison exercise, the standard 'health warnings' must be considered. Every farm is unique and so like is not being compared with like. The relative rankings of the farm do not imply anything more than their situation at the time of the study, as the assessment takes no account of crop rotations and other factors such as any crop stressors (e.g. pests and diseases, drought etc.) which may have increased inputs or the relative produce prices which will also affect the relative rankings. These parameters are likely to be more pronounced given that the farms are spread across Europe, a very large and varied geographical area. However, this academic study was not intended to compare the relative performance of farms but to compare the performance of the individual tools.

A number of conclusions can be drawn from the comparison exercise. Firstly, as highlighted by Franks and Haddingham (2011) the choice of FU alters how the emissions status of the farm is interpreted. No single FU addresses all the needs of sustainability, incorporating, for example, other environmental and social issues. Three FUs were used in this study but others could have been added such as the total energy in farm produce measured as the crops metabolised energy content or by the crops protein content, a measure of food quality (Franks & Haddingham, 2011) and these may have broadened the assessment and provided more insight from a sustainability perspective. However, it is probable that additional FUs would have produced yet other variations in the rankings of the case study farms and therefore it is vitally important that the chosen FU meets the needs of the assessment end use i.e. it is fit for purpose. It is also important that before such tools are used in any way that might reward or penalise farmers based on their GHG emissions consensus is reached as to which FU is used and that the wider sustainability objectives are considered such as food security.

Secondly, the farm comparison exercise shows that the quantitative emissions data generated by the tools examined is hugely variable and this may well lead the end user to distrust the results which will not help the adoption of climate friendly farming practices. Generally, most assurance schemes will use a specific tool and temporal trends should be reasonably sound but this is not always the case and some benchmarking schemes rely on individuals submitting their own data into core systems in order to build up large data sets on which benchmarks are based. This latter approach should obviously be avoided until the tools are better harmonised.

Climate change, and societal responses to reduce atmospheric concentrations of GHGs, is undoubtedly a key challenge of the 21st century, but which must be met alongside addressing the demands of other issues such as food security. Sustainable farming is about finding an acceptable balance between multiple social, economic and environmental objectives. Consequently the industry needs credible, robust and consistent tools to support decision making at the farm, industry and policy levels. Actions to reduce GHG emissions or increase carbon sequestration need to be based on sound scientific knowledge in the context of adopting the most cost effective options. Carbon calculators have an important role to play in helping to meet climate change objectives and to help deliver more sustainable farming practices. However, it is evident that there is a need for greater harmonisation across the tools in terms of emission factors, methodology, functional units, boundaries and practices included to reduce the differences between the outputs. In so doing it will provide for a more common perspective for all stakeholders involved in the development of a more sustainable food production system. To this end the authors would advocate the development of standards for carbon accounting tools and not just the calculation method. In the absence of such guidance it is important that the tool used is carefully selected based on the end users aims and objectives and the results obtained are not seen as definitive.



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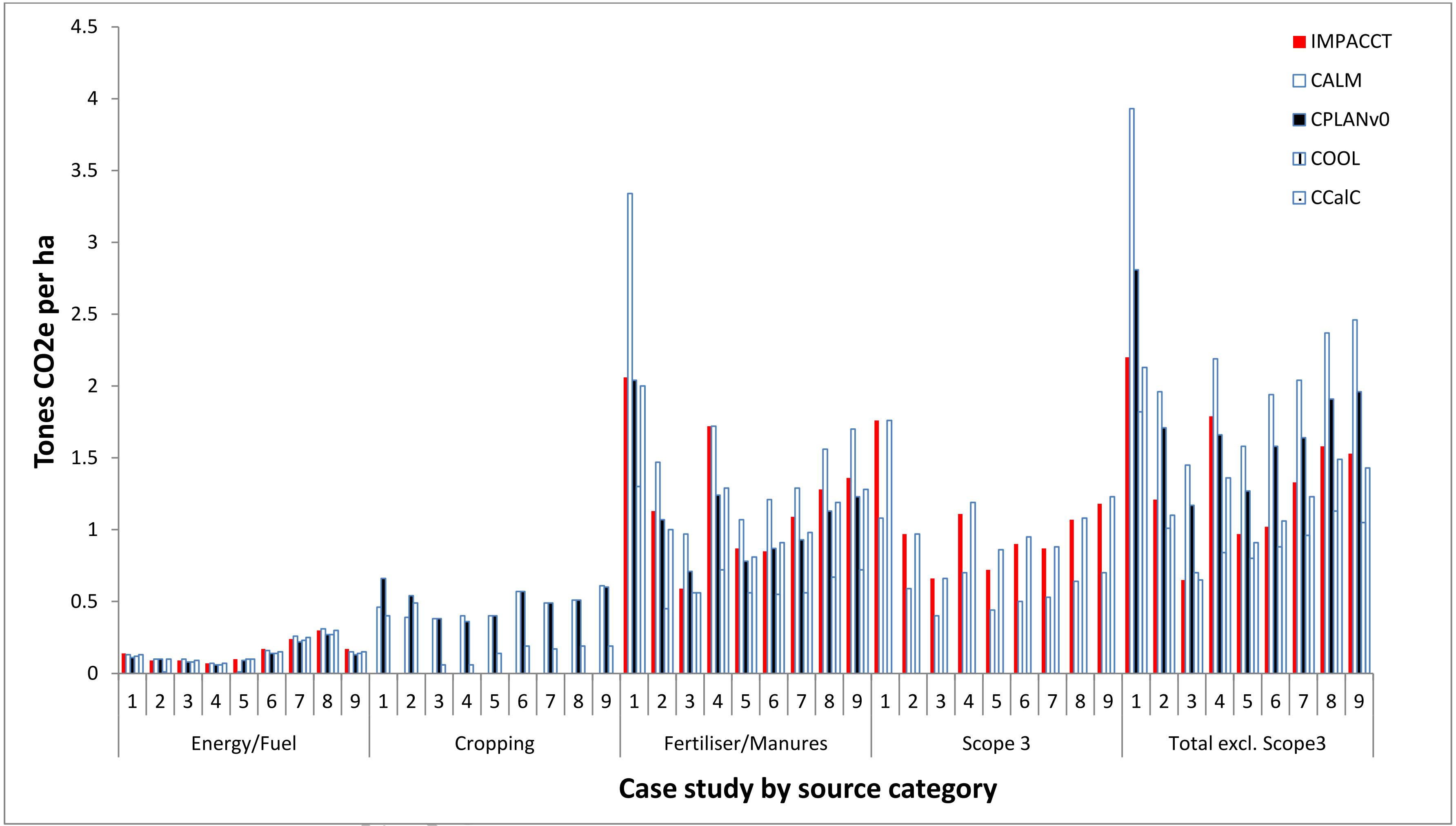



**Figure 1: Emissions per hectare**

Figure 2a: Ranking of case study farms per hectare by different tools

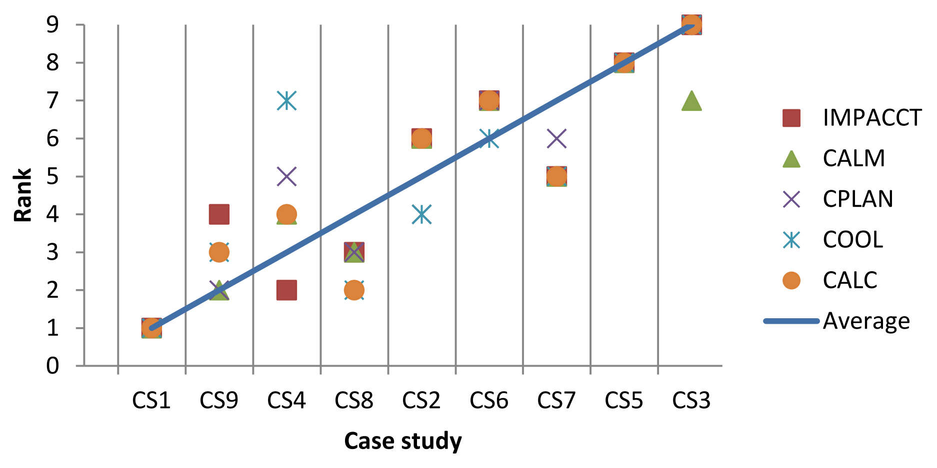
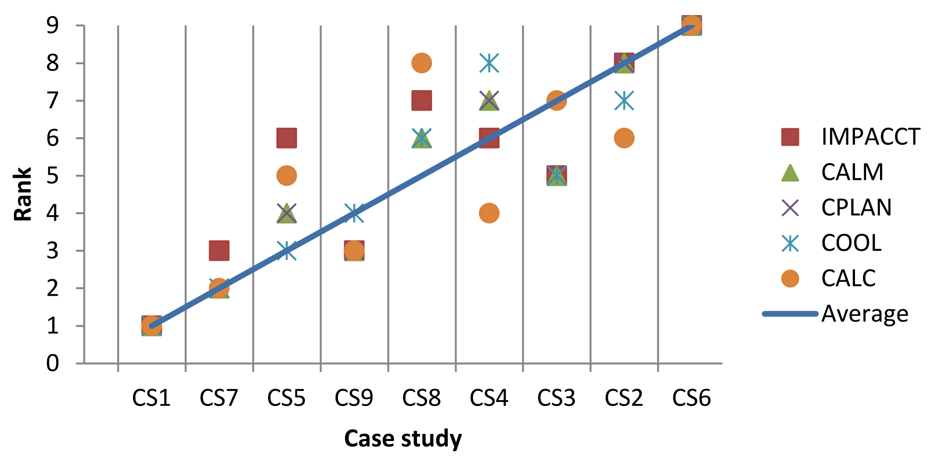



Figure 2b: Ranking of case study farms per tonne by different tools



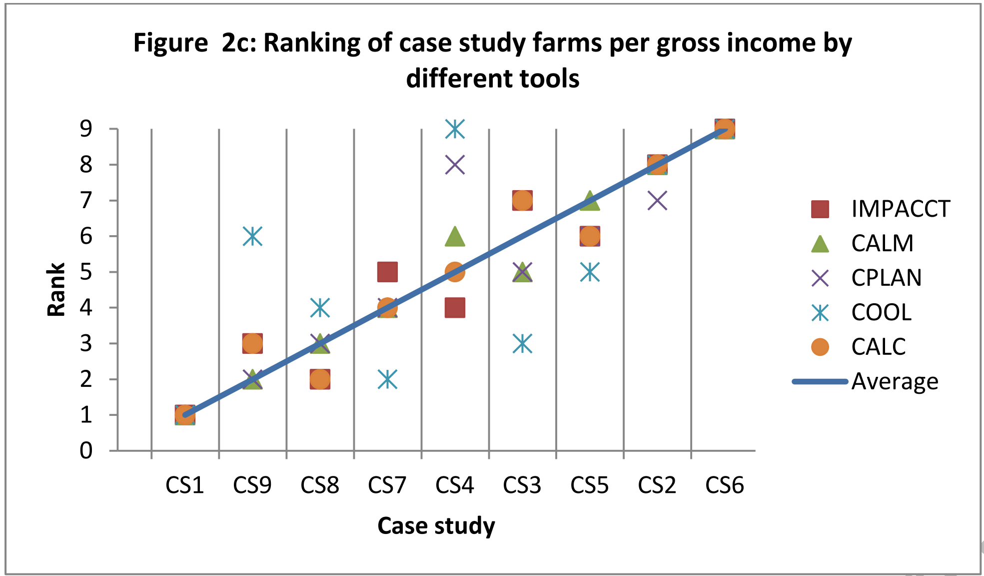


Figure 2c: Ranking of case study farms per gross income by different tools
Rank
9
8
7
6
5
4
3
2
1
0
CS1
CS9
CS8
CS7
CS4
CS3
CS5
CS2
CS6
Case study
IMPACCT
CALM
CPLAN
COOL
CALC
Average

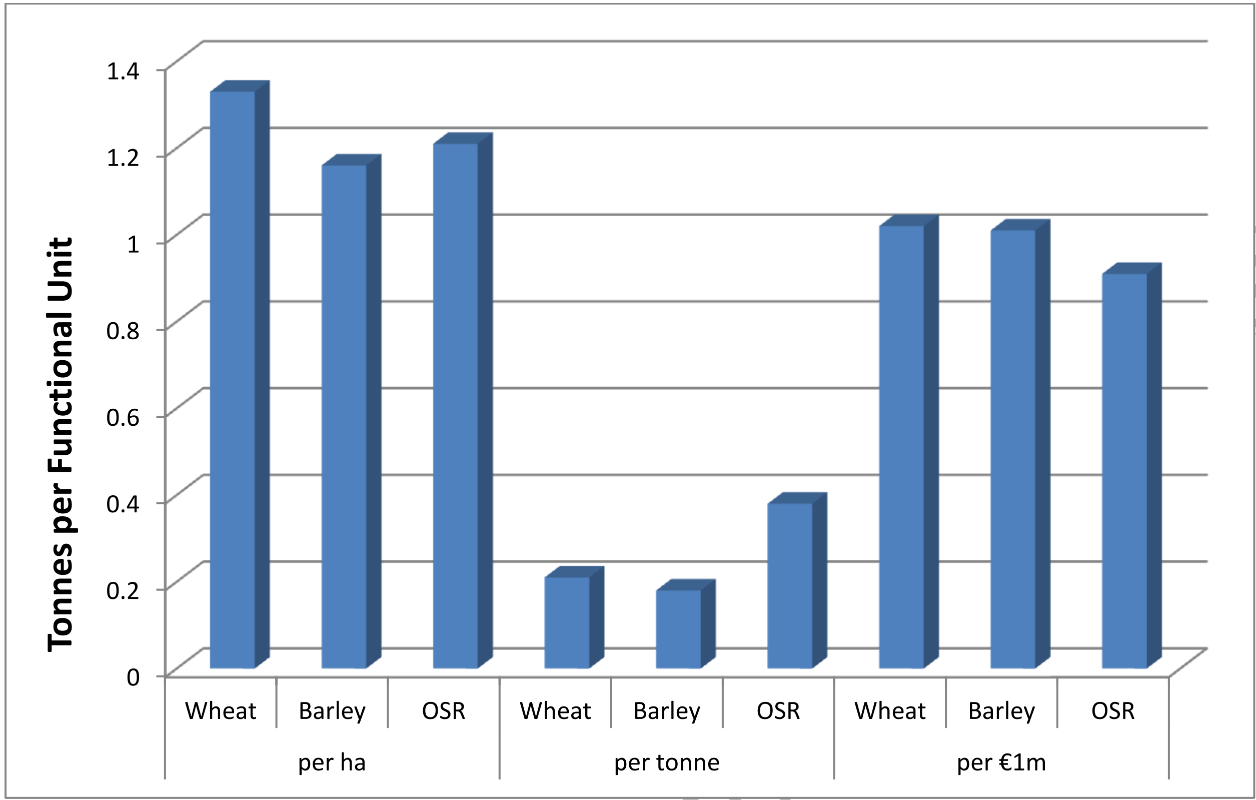



**Figure 3: Gross emissions per crop averaged across tools and case studies**