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Agricultural climate change mitigation: carbon calculators as a guide for decision making

The dairy industry is receiving considerable attention in relation to both its significant greenhouse gas (GHG) emissions, and it's potential for reducing those emissions, contributing towards meeting national targets and driving the industry towards sustainable intensification. However, the extent to which improvements can be made is dependent on the decision making processes of individual producers, so there has been a proliferation of carbon accounting tools seeking to influence those processes. This paper evaluates the suitability of such tools for driving environmental change by influencing on-farm management decisions. Seven tools suitable for the European dairy industry were identified, their characteristics evaluated, and used to process data relating to six scenario farms, emulating process undertaken in real farm management situations. As a result of the range of approaches taken by the tools, there was limited agreement between them as to GHG emissions magnitude, and no consistent pattern as to which tools resulted in the highest/lowest results. Despite this it is argued, that as there was agreement as to the farm activities responsible for the greatest emissions, the more complex tools were still capable of performing a 'decision support' role, and guiding management decisions, whilst others could merely focus attention on key issues.

Keywords: carbon calculators; climate change mitigation; livestock agriculture; greenhouse gas emissions; decision support

Introduction

The potential consequences of anthropogenically driven climate change are both severe and varied, encompassing threats to the environment, food production, the economy and human health (Araújo, Alagador, Cabeza, Nogués-Bravo, & Thuiller, 2011; Kim & Neff, 2009). Inevitably therefore, it has been at the forefront of both national and international environmental policies ever since 1997, when the Kyoto Protocol established a greenhouse gas (GHG) emissions reduction target of 5.2% below 1990 levels (for 37 developed nations - Lewis, Green, Warner, & Tzilivakis, 2013). The European Union (EU) for example, has set ambitious targets for its member states, with the 2020 Climate and Energy Package aiming to reduce emissions by 20% by 2020 (European Commission, 2007; European Commission, 2008), the 2030 Climate and Energy Framework going for 40% by 2030 (European Commission, 2014), and the 2050 Low-Carbon Economy Roadmap (European Commission, 2011; Franks & Hadingham, 2012) targeting 60% by 2040 and 80% by 2050 (all compared to 1990 levels). Progress towards the early targets has been good (European Environment Agency, 2015), but it is clear that all sectors will have to play their part if this is to continue; therefore, as well as addressing major emitters of carbon dioxide (CO_2 - such as the energy industry), policies such as the UK's Carbon Plan (HM Government, 2011) now recognise the role to be played by businesses more broadly, including those in the agricultural sector.

Although some agricultural activities (especially those associated with grassland agriculture) can support significant carbon storage, others can be major contributors to GHG emissions. The IPCC (Intergovernmental Panel on Climate Change - Smith et al., 2014) for example, estimates that agriculture as a whole accounts for between 10% and 12% of all anthropogenic GHG emissions around the world, with similar estimates of 9% having been produced for the European Union (European Commission, 2012) and UK (AEA, 2011). As far as the dairy industry is concerned, estimates of the scale of the problem vary, but the FAO (who adopted a life cycle assessment approach encompassing a wider range of emissions than the above studies - O'Mara, 2011), suggested that the sector could be responsible for 3% to 4% of emissions (FAO, 2010; Gerber et al., 2013). Unlike in many other business sectors however, CO_2 is not the major cause of concern, albeit that some is emitted as a result of the energy used in farm machinery, milking parlours, animal housing and refrigeration, for example (Crosson et al., 2011; Hillier et al., 2011; O'Mara, 2011). Instead, the main issues relate to methane (CH_4) emitted due to enteric fermentation and the breakdown of stored manures, and nitrous oxide (N_2O) produced as a result of the application to land, and subsequent breakdown, of nitrogen-based fertilisers and manures (Crosson et al., 2011; Hillier et al., 2011; O'Mara, 2011; Paustian et al., 2004), both gases having significantly higher global warming potentials (GWPs) than CO_2 itself (25 CO_2e and 298 CO_2e respectively).

Dairy agriculture therefore, plays an important role in driving climate change, and as a result its impact is now a focus of concern for a number of countries (Franks & Hadingham, 2012; Hagemann, Hemme, Ndambi, Alqaisi, & Sultana, 2011; Hillier et al., 2011; Smith et al., 2014). There can be little doubt that there will be no let up on the pressures being placed on the industry to improve performance as a result of the ambitious GHG reduction targets being set by domestic and international legislation (see above), since meeting these targets is going to become increasingly difficult. Not least because some of the other most polluting sectors have already achieved substantial decreases in emissions in recent years. In the UK for example, there has been an estimated 38% decrease in total GHG emissions since 1990, with some of the biggest contributors being amongst those sectors responsible for most of the countries emissions (e.g. the energy supply sector has seen a 41% reduction since 1990 - DECC, 2016). Agriculture has seen a 16% reduction, but much of this was down to a reduction in livestock numbers and synthetic fertiliser use in the late 1990s, with little improvement since (DECC, 2016).

Fortunately however, options for climate change mitigation within the dairy sector, particularly in developed nations such as those of Europe and North America, are reasonably good (Hillier et al., 2011). Indeed many mitigation options make use of technologies and/or techniques which are already available, and so could be implemented quite quickly (Crosson et al., 2011). It is known, for example, that amendments to animal diets can affect enteric CH_4 production, the extent to which livestock are grazed and/or housed impacts N_2O emissions, and that changes to the way in which manures and/or slurries are managed can affect emissions of both gases (O'Mara, 2011). Consequently, the FAO estimates that within the livestock sector as a whole, a 30% reduction in GHG emissions could be possible in any given system, region and climate, if producers adopted the technologies and practices currently embraced by the best performing 10% (Gerber et al., 2013). Although the estimated benefits of such amendments do vary considerably (Smith et al., 2014).

This however, needs to be achieved against a backdrop of increasing pressures for agriculture (including livestock agriculture) to produce more food in light of food security concerns (Firbank, 2009). Global population, which is already around 7.5 billion, is forecast to continue growing, and be in excess of 8.5 billion by 2030, 9.7 billion by 2050 and 11 billion by 2100 (UN DESA, 2017; Crosson et al., 2011; O'Mara 2011; McAllister, Beauchemin, McGinn, Hao & Robinson, 2011; Campbell, Thornton, Zougmoré, van Asten & Lipper, 2014), which will inevitably drive a significant increase in demand for food (Tilman, Balzer, Hill & Befort, 2011). In addition however, it is to be hoped that the levels of extreme poverty which today blight the lives of millions of people worldwide, continue to fall as they have in recent decades (particularly in Asia - World Bank, 2016; Campbell et al., 2014), such that demand will rise still further. Consequently, the Food and Agriculture Organization predicts that global food supply will need to increase by nearly 40% by 2030 and 60% by 2050, and even more than this in the developing world (from 2005/2007 figures - Alexandratos &

Bruinsma, 2012). Consumption of livestock products (principally meat, but also dairy) however, tends to be related to living standards (Foresight, 2011; Campbell et al., 2014), so as these improve such consumption is expected to rise at a rate in excess of that for food as a whole, so that by 2050, demand for livestock derived products of all types could be at twice their current level (McAllister et al., 2011), with potentially serious implications for the future of GHG emissions from the industry (Garnett, 2009).

In the second half of the 20th century, agricultural production around the world increased sufficiently to keep pace with the increased population, although clearly there were significant issues to address when it came to the equitable distribution of supplies (Pretty, Toulmin & Williams, 2011; Firbank, Elliott, Drake, Cao & Gooday, 2013). However, the capability of the industry to meet this demand is threatened by a lack of potentially productive land that isn't already being utilised (Firbank, 2009), and even where there is availability, the environmental costs of bringing it into production could be considerable (Tilman et al., 2011; Petersen & Snapp, 2015). In addition, in many areas the productivity of existing farmland is likely to fall due to the combined effects of soil degradation, urbanisation, climate change, sea level rise and increased competition for resources, whilst still more may be required for the production of energy crops (Firbank, 2009; Campbell et al., 2014). These and other environmental threats, present a serious challenge for the future development of the global agricultural sector, but it is clear that a means needs to be found to increase productivity whilst protecting the environment, and (in as far as climate change is concerned) playing a role in mitigating the problem, as well as ensuring the long-term resilience of the sector (Firbank, 2009; Pretty et al., 2011). This has led to the concept of sustainable intensification (SI), which was first coined in the 1990s (e.g. Pretty, 1997), and in which food supply is increased, but without the need to bring additional land into production or incur the environmental costs that have often been associated with agricultural intensification in the past (Firbank, 2009; Foresight, 2011; Firbank et al., 2013; Petersen & Snapp, 2015). Indeed, some authors have used the term to indicate agriculture that both increases food production, and contributes to the delivery of a whole range of ecosystem services (i.e. something that goes beyond simply avoiding environmental damage - Foresight, 2011; Firbank et al., 2013; Campbell et al., 2014). The related term of climate-smart agriculture (CSA) has also been used by some authors with narrower climate change based objectives (e.g. the FAO - Franks, 2014), including both the mitigation of and adaptation to climate change (Campbell et al., 2014). Indeed it could be argued that SI is an essential element in CSA and vice versa, in that the use of resources more efficiently in production (SI) inevitably has a role to play in moving farming towards CSA, whilst at the same time, where CSA is practiced successfully, it will simultaneously result in SI (Campbell et al., 2014).

It has been suggested that in under-yielding parts of world (such as many in the developing world), there is scope for improvements in both yield and environmental performance through the adoption of technological improvements (Tilman et al., 2011), indeed, there are clear examples from the developing world in which SI has been demonstrated in practice (Pretty et al., 2011). In the developed world too, it has often been put forward as a key priority for agricultural development (Foresight, 2011; Franks, 2014), but here it is often viewed as something that will be desirable in the future rather than something to be strived for in the present (Firbank et al., 2013). Indeed, there is considerable confusion as to precisely what SI involves when implemented on the ground, in part due to the lack of a uniformly applied definition of what actually defines sustainability and what would be required to get there (Petersen & Snapp, 2015). There is also little agreement as to whether it will entail a profound shift in production system, or whether it can be achieved through relatively minor amendments to current practices (Petersen & Snapp, 2015). As a consequence, SI is often seen as something which sounds good at the policy level, but which means considerably less to those who would be responsible for delivering it (Petersen & Snapp, 2015). Yet if the needs of global food security are to be met, it is likely that in addition to major improvements in food productivity needing to be made in parts of the developing world, the developed world too will have a significant role to play, and the pressure to maintain or increase productivity in an ever more challenging climatic situation, and without resulting in increased environmental damage, is already being felt (Firbank et al., 2013).

Whether individual farm businesses make the changes to their practices necessary to influence climate change and move towards SI/CSA is, however, determined by the decision making processes of individual farmers, so in recent decades attempts to understand and influence those processes, have become central to agri-environmental policy in the UK, Europe and more widely (Sutherland et al., 2012). Some studies indicate that it is the economic benefits of implementing environmental friendly practices which are key to their adoption (Sutherland, 2010), although this may be an oversimplification of thought processes which are influenced by a wide variety of external and internal factors, many of which do not relate to economics. Farmers are a heterogeneous group with a range of priorities (Ingram, Gaskell, Mills, & Short, 2013), so whilst economics will always be a powerful motivator for farmers incorporating agri-environmental schemes into their business plans, it is not the only one. Studies of farmer motivations have found that by far the most important consideration is the desire to be able to pass the business on to subsequent generations (continuance), although the precise meaning of this varies from business to business (Ingram et al., 2013). Some do judge it purely in terms of economic factors (profitability), whilst others consider such things as the maintenance of traditional production methods (Ingram et al., 2013), and consequently, although there is often little evidence of influence in the form of social pressures to become involved in environmental improvement per se (Sutherland, 2010), environmental benefits may accrue from decisions made for other reasons. Conversely however, there is also a desire to be seen as a ‘good farmer’, often evidenced by high yields, tidy fields, good quality livestock, and so on (Sutherland & Darnhofer, 2012), which could in some cases work against the adoption of environmentally friendly practices. An additional complication results from the fact that most farm businesses do not operate within a framework in which it is possible to make fully rational decisions as to how a farm should develop through time (for example whether to implement GHG mitigation measures, and if so which ones). Instead, many are locked into a specific direction of travel, within which only gradual transition is possible, due to so called ‘path dependency’, a process in which historical events (e.g. investment decisions) can restrict the ability to change direction (Sutherland et al., 2012). As a result, any change in practices is likely to occur incrementally, unless forced by a significant trigger event (e.g. legislation, economic pressures, etc.).

Whether occurring as a result of gradual, incremental change, or a major trigger event however, if businesses are to take up the challenge of climate change mitigation (for example), then they need the tools and advice to enable them to integrate the necessary changes into their management protocols. In relation to many of their practices (particularly those related to production), farmers may be sufficiently confident in their own abilities as to mean that external advise and/or information may not be sought, and where it is, it may be only once a decision on ‘what to do’ has been made and specific financial or technical advice is required (Beedell & Rehman, 1999).

Despite this however, knowledge transfer (or ‘agricultural extension’) between researchers and agricultural practitioners, has long been seen as essential in order to ensure that farmers have access to the up-to-date information they need (Reardon-Smith et al., 2014). Traditionally this was done through the provision of face-to-face advice, provided either by the state or privately; however, such systems are limited in their ability to engage with large numbers of producers in a cost effective way, particularly in large, relatively sparsely populated parts of the world (Reardon-Smith et al., 2014). Consequently, state funded systems have often been curtailed or even ended altogether, and the business expenses involved in commercial provision can be seen as a major barrier to uptake (Dodd, 2012; Lewis et al., 2013). Much more use is therefore made (as it is in in most other areas of life) of ICT (information and communications technology), with an explosion in both internet-based and stand-alone (and sometimes paper-based) decision support tools, designed to take complex modelling approaches and/or expert judgement (Reardon-Smith et al., 2014) into the homes and offices of farmers. Albeit that the adoption of such systems by the agricultural industry has, to date, been piecemeal, which is possibly a reflection of their perceived (or real) inability to reflect complex site and business-specific issues (Reardon-Smith et al., 2014). Variability of environmental impacts between farms which, on the face of it, are operating the same production system, has been shown to be large, and the impact (positive or negative) of introducing environmental measures can be highly site and/or enterprise specific, and depend on complex interactions between farm practices (Meul et al., 2014). Consequently, in relation to GHG emissions for example, generic assessments of their magnitude and/or cause, and therefore potential solutions, may be of limited business value (Lewis et al., 2013), with farmers instead needing advice which is tailored to their enterprise (Meul et al., 2014).

In part, this has been addressed through the development of a range of carbon calculators for use in carbon accounting (or carbon footprinting). This in itself, is not a new concept (it has often been associated with life cycle assessment investigations), and involves estimating GHG emissions over a pre-defined time period, often a products life cycle or, more commonly in agriculture, a production season or calendar year. At their simplest, these carbon calculators can be used to raise awareness of the important issues and sources of GHGs within a farm business (Kim & Neff, 2009; Lewis et al., 2013; Whittaker, McManus, & Smith, 2013); however, they can also be used as a basis for reporting emissions (e.g. to a purchaser further down the supply chain), or more importantly (in the context of this paper) to evaluate mitigation options (Whittaker et al., 2013). This requires producers to go beyond merely identifying their emissions, to identify potential mitigation activities, and make informed choices between them (Franks & Hadingham, 2012). This paper examines a number of the tools aimed at (in whole or part) the European dairy sector, in order to determine the extent to which they provide the sort of information likely to be of value in this sort of practical business decision making. In so doing, it considers whether the examined tools are suitable for inclusion within farm management procedures, or whether the information provided is of too general a nature to provide a basis for land and business management decision making, albeit that such systems may still have a role to play in informing users of the key issues more generally.

Material and methods

The methodology employed for this study is comprised of two main elements. Firstly, the selection of carbon accounting tools for further in-depth analysis, and their characterisation with respect to various properties relating to their ability to provide information on which climate change mitigation strategies could be based. Secondly, a consideration of the outputs of the various tools in relation to a series of standardised production scenarios, so as to identify the extent to which they provide a sound, consistent basis on which to make management decisions.

Carbon calculator identification & characterisation

In recent years, the number of carbon accounting tools available has increased significantly, such that they are now available for use in a wide variety of sectors (agricultural, domestic, industrial, transport, etc.) and by different end-users with different agendas and needs (e.g. policy makers, scientists, environmental managers, practitioners, etc.). The same can be said of the number of tools available for the agricultural industry in particular, with reviews of those available to agriculture and forestry carried out by Little and Smith (2010), Colomb et al. (2012) and Denef, Paustian, Archibeque, Biggar and Pape (2012) identifying 10, 18 and 36 respectively (as well as other protocols, guidelines and models). Not all are appropriate for adoption in the dairy industry however, so in order to clearly identify those which at least purport to be suitable for use in the sector under study, a review of available systems was carried out, in which tools were sought (through published literature and on-line) which met a number of criteria, and which reflected the different approaches taken (see below). In particular, it was determined that they should:

- Have data entry and computational capabilities appropriate to the dairy sector: It is essential that tools have data entry systems and emission factors that allow emissions from dairy agriculture, as well as those from general energy use, to be determined.
- Be applicable to the region being considered: In order to allow a degree of inter-scenario/inter-tool comparison, it was essential to ensure that production was of

a similar type and/or faced similar geographical conditions. Consequently, the study was restricted to those tools suitable for use in European dairy agriculture.

- Be based on easily accessible data: Agricultural businesses face considerable pressures on staff time; therefore, if maximum adoption of carbon calculator use as a technique is to be achieved, data entry requirements should be such that, in as far as possible, only data likely to be easily available on the majority of farms is required.
- Be freely available: Equally financial pressures mean that costly tools and models are unlikely to achieve wide-scale market penetration within the dairy sector. Consequently, this study was restricted to those tools which are freely available, although it is recognised that in some cases more detailed, commercially available systems may be appropriate (e.g. when used by a farm advisor).

Each of the tools selected for further evaluation was examined in depth in order to identify a series of key characteristics (Table 1 - key elements of which are discussed in this paper) which were used to determine ease of use, site and business specificity, and the extent to which climate change mitigation options are guided so as to assist in management decisions.

(Table 1 near here)

Production scenario evaluation

A number of livestock farm production scenarios were developed from data collated on real farms as part of a pan-European research project carried out on behalf of the European Commission (Tzilivakis, Lewis, Green, & Warner, 2010). Those case-studies in which the principal enterprise was stated to be dairy production were identified and reviewed in detail, so as to develop standardised scenarios in which on-farm data was recorded in a consistent form. To do this, those elements of a farms activities which were directly related to the dairy part of the enterprise were isolated (i.e. anything which could be wholly assigned to arable production or other forms of livestock was removed), and all relevant data was extracted from that part of the scenario. Gaps in data which might impact on the ability of some tools to be fully tested were then identified, and filled using published literature related to land and animal management in the dairy sector (e.g. Defra, 2010; Natural England, 2012; Natural England, 2013; Thomas, 2007), and the characteristics of the dairy industry in different EU countries (e.g. European Commission & EU FADN, 2013). In addition, supporting data on the local climate and soils was identified from freely available databases. In the case of climate, these belonged either to the local meteorological service (UK: the Met Office - Met Office, n.d.; France: Meteo France - Meteo France, n.d.; Italy: Meteo Aeronautica - Meteo Aeronautica, n.d.), or the World Weather Online database (Poland - World Weather Online, n.d.). Soils data was obtained in the form of the 'soil reference group code from the World Reference Base (WRB) for soil resources' and the 'dominant surface textural class', both available from the European Soil Data Centre (ESDAC - Panagos, Van Liedekerke, Jones, & Montanarella, 2008).

The approach of developing scenarios in this way (as opposed to using the case-studies in their existing state) was adopted, in order to overcome the different approaches to data recording (reflecting local practices) taken in the original project, allow for gaps in data resulting from the specific requirements of that study, and permit greater comparability. Each of the tools identified for detailed study was then used to produce a GHG emission estimate and profile (broken down by broad source category) for each scenario, emulating processes that would be undertaken in real farm management situations. In each case GHG emissions were apportioned in a number of different ways, namely:

- Total GHG emissions of the farm: Emissions not apportioned.
- GHG emissions per productive farm hectare: Taken to be emissions divided by the area of grassland and arable (for feed) crops.
- GHG emissions per livestock unit: Livestock units (LU) being based on livestock numbers, and calculated according to (Redman, 2016 - Table 2).
- GHG emissions per unit of milk production: Emissions divided by milk yield in m^3.

(Table 2 near here)

GHG emission profiles were plotted for each tool, scenario and method of emission apportionment, in order to facilitate a rapid visual comparison of results. In each case, scope 3 emissions were ignored in this part of the study, so as to allow comparisons between calculators to be made on an equal basis, since not all allowed scope 3 emissions to be calculated (see below). In addition, comparative plots of the ranges produced by the various assessed tools, for each of five broad categories of emission source (energy/fuel use, crop residues, livestock, nutrient application, others), were produced for each scenario, in order to aid in the identification of commonalities and differences between tools.

Results

Carbon calculator identification & characterisation

A thorough review of the carbon accounting tools available for farmers identified seven which met (to at least a reasonable extent) the criteria established above. A number of others were considered for inclusion, but rejected on one of a number of grounds. Some were deemed not to be sufficiently applicable to mainstream European agriculture, including a number produced in the US (e.g. COMET-Farm - USDA, n.d.), Australia (e.g. the Farming Enterprise Greenhouse Gas Emissions Calculator - The N_2O Network, n.d.; and the FarmGAS Calculator ST - Australian Farm Institute, n.d.) and New Zealand (e.g. the Carbon Farming Calculator - Carbon Farming Group, 2012). Others (the HGCA's Carbon Footprinting Decision Support tool for example - Collison & Hillier, 2012) were found not to cover the dairy sector, were limited in extent (e.g. relating only to emissions associated with direct energy use - Centre for Alternative Land Use, 2007), or were excluded on the basis that a fee was required to gain access to the system (e.g. CPLANv2 - CPLAN, n.d.). Nevertheless, those that were taken forward to the next stage of the study included a range of formats and complexities, as detailed below and in Table 3.

- CPLANv0 (CPLAN, n.d.): Developed by farmers in central Scotland for use by UK based farm/land managers and policy makers, principally as a management tool for assessing and monitoring GHG emissions/sequestration on farm and for informing policy. It is the simplest of the tools assessed in this part of the study, requiring only limited data input through a simple web-based interface. As a result however, there is also limited depth in, or breakdown of, the outputs to the system, with only broad categories of emissions being reported, and specific mitigation advice is not provided. One bug was identified within this tool, as where numbers of 'other cattle < 1 year' were entered the emissions calculated (for that element only) were in CO_2eq, rather than the Ceq the results were stated to be in. Adjustment was made for this in this paper, although it is unclear whether users will generally be aware of the problem.

- CALM (Country Land and Business Association, n.d.): Developed by the UK's Country Land and Business Association (CLA), to allow UK farm/land managers to identify suitable options for cutting GHG emissions and increasing resource use efficiency. It's a free online system, but requires site registration, allowing assessments to be saved and retrieved. It also requires a greater level of input data than CPLANv0, although its online nature means that needs are by necessity still relatively light. As a result however, CALM breaks down output data to a greater extent, although specific mitigation advice is not provided.
- CCaLC (The University of Manchester, n.d.): An application (previously MS Excel based) developed by the University of Manchester for use in all forms of production (i.e. not just agriculture), but which encompasses primary production. In the main it is intended for use by UK supply chain managers wishing to optimise or monitor supply chains (although the functional unit can be defined by the user - e.g. a farm, a product type, etc.), and as such it may not be particularly user-friendly when it comes to on-farm users. There is a reasonable amount of breakdown in the results (although sequestration is not accounted for), and if required the same tool can be used to address other resource efficiency issues (i.e. water use efficiency). Applied manures and slurries are entered in kg, with no allowance being made for variations in nitrogen (N) content; but inorganic fertilisers are entered in terms of N applied. Specific mitigation advice is not provided.
- COOL Farm Tool (Cool Farm Alliance, n.d.): An online tool (previously MS Excel based), the GHG element of which was developed for the Cool Farm Alliance by a team led by the University of Aberdeen, in order to allow options for cutting emissions and increasing efficiency to be identified by farmers and

supply chain managers/companies around the world. Much of the required input data is likely to be readily available, but data requirements are again reasonably high, and the international audience of the tool means that some may not be immediately available in the form required. Allowance is made for the type and dry matter content of feed, and manure and slurry applications are entered by type (with default N contents), whilst inorganic fertiliser applications can be entered by product type and amount (again with default N contents) or nutrient amount. There is a limit to the number of farm enterprises which can be saved in the free version (although subscription services are available), and a whole-farm assessment may require the summing of the results from a number of enterprise assessments. There is a reasonable level of breakdown in the results (by gas and source), although specific mitigation advice is not provided.

- IMPACCT (University of Hertfordshire, 2010): A MS Visual Basic based application developed by the University of Hertfordshire to aid European farmers/land managers in assessing GHG emissions and sequestration, and to provide advice on appropriate mitigation strategies. This system too has relatively high data requirements (although much is likely to be readily available), but emissions and sequestration data (which can be saved and retrieved) can be broken down by gas and source, plotted, and recommendations obtained for practical on-farm measures for reducing emissions and/or increasing sequestration. Organic manure and slurry applications are entered by type (default N content used) and inorganic fertilisers as N, whilst livestock diets are selected from a limited number within the tool's database (the tool having been developed as, to some extent, a proof of concept). In a contrast to the other tools assessed, energy use is estimated from entered fuel types and farm operations, rather than directly from entered fuel use.

- Farm Carbon Calculator (Climate Friendly Food, 2012): A web based system (which allows the saving of a limited number of assessments online) developed by a non-profit organisation, to promote low carbon practice amongst UK farmers and growers, and forming part of the wider Farm Carbon Cutting Toolkit (Climate Friendly Food, n.d.). Although heavily influenced by the needs of organic producers, it is nevertheless equally applicable to the wider industry. Data requirements are moderate, but there is no breakdown of the results by gas. Inorganic fertilisers are entered in tonnes of product and manures/slurries are accounted for through an assessment of production as opposed to that applied. This tool also allows the assessment of a wide range of other farm activities (including fencing, pipe laying, etc.) and those associated with capital items and distribution, although to maintain comparability this facility was not used in this study.
- European Carbon Calculator (Bochu, Metayer, Bordet, & Gimaret, 2013): An MS Excel based system developed by Solagro in France for the European Commission's Joint Research Center (JRC), with the aim of publicising GHG emissions from farming practices at a farm scale, and proposing mitigation actions (Bochu et al., 2013). Data requirements are high (including those associated with climate and soils - some of which may not be easily accessible). The flipside of the heavy data requirements is that the resulting emissions and sequestration data can be broken by gas and source and plotted, and it is possible to obtain recommendations for mitigation. In terms of suggesting mitigation options, the spreadsheet quantifies the potential tCO_2e saving per ha per year

(and percentage saving) and where appropriate makes an estimate of the possible financial savings, associated with a number of options (e.g. no-tillage, optimisation of grazing, etc.).

(Table 3 near here)

Production scenario evaluation

Six case-study farms were identified as being predominantly dairy-based and were therefore selected as the basis on which to develop a series of standardised scenarios. Data on the dairy production and other (climate, soils, cropping, nutrient management, etc.) characteristics was then collated for each scenario in as consistent a form as possible (Tables 4 to 6).

(Tables 4 to 6 near here)

When the GHG emission profiles (broken down by broad emission source category) for the six scenario farms using four different apportionment techniques (Figure 1), and the comparative ranges produced by the various assessed tools for each source category (Figure 2) were plotted, the following key issues were highlighted. Firstly, it is evident from these results, that there is clearly (and perhaps unsurprisingly) a significant difference in the estimates of total GHG emissions (Figure 1a) for the different farm scenarios. Although it is noticeable that this is greatly reduced when the estimated GHG emissions are related to some practical functional unit, whether that be an area-based unit (e.g. productive area of the farm - Figure 1b), an animal-based unit (e.g. number of livestock units - Figure 1c) or a production-based unit (e.g. milk production - Figure 1d). However, as discussed below, the relevance of this in terms of on-farm management decisions, may be limited

Secondly, it is clear that in terms of the estimates of total emissions (and therefore those associated with the various functional units) for individual farm scenarios (intra-scenario comparisons), there is considerable variation in the figures produced, with the percentage difference between the maximum and minimum estimates (Table 7 - defined as in Equation 1) being between 41.57% for scenario FR2 and 73.22% for scenario UK1.

$$[(\max - \min) / \text{mean}] \times 100 \qquad (1)$$

Particularly noticeable (Figure 1) are the fact that CPLAN results in an unusually high GHG emission estimate (in comparison to the other tools) for scenario UK1, whereas the COOL Farm Tool results in an unusually low estimate for scenario IT1, both of which appear to be a function of the way in which emissions from the livestock themselves (e.g. those from enteric fermentation) are assessed in these tools. However, these are far from the only differences between tools, which is a reflection of the differing methodologies and approaches taken, as well as the amount of entered data utilised.

(Table 7 near here)

There is also no consistent inter-scenario pattern in terms of which calculators produce the highest/lowest GHG emission estimates. Although the COOL Farm Tool produces the lowest estimates for three of the scenarios (FR1, IR1, UK1) with another two being produced by IMPACCT (FR2, PL1), the highest estimates are split equally between CPLAN, CCalC and the Farm Carbon Calculator, with two each.

Despite the above however, it is clear from Figure 2 (and to a lesser extent Figure 1) that in the main, there is little disagreement as to which elements of the farms activities are responsible for the bulk of the GHG emissions. In the case of these dairy farms, this is down to the livestock themselves (e.g. through enteric fermentation), with this category of emissions accounting for between 35.5% (the Farm Carbon Calculator and scenario PL1) and 96.2% (CPLAN and scenario UK1) of the calculated emissions (mean = 69.1%, standard deviation = 13.5%), which is a clear indication of the important relationship between livestock numbers and GHG emissions noted previously by O'Mara (2011). In contrast emissions resulting from cropping activities, other activities (e.g. pesticide use) and in the main direct energy use, were relatively low. The exception to this in the latter case, was in relation to scenario PL1, which had considerably higher than expected fuel consumption. For this scenario IMPACCT resulted in a significantly lower emission estimate than any other tool, as a result of the fact that unlike other tools, IMPACCT doesn't account for fuel use directly, but instead by estimating it from the practices occurring on the farm. Consequently, if a farm falls well outside of the norm in this respect, it may not be picked up. Emission estimates associated with nutrient application (fertilisers and manures) demonstrated the most variation, accounting for between 1.7% and 51.9% of the GHG emissions calculated for a given scenario (mean = 15.1%, standard deviation = 11.51%); with the Farm Carbon Calculator producing consistently higher estimates (associated with emissions due to the use of inorganic fertilisers) than any other tool. Emissions due to cropping are only significant in CCalC and the European Carbon Calculator.

(Figures 1 & 2 near here)

Discussion

It is clear from the above results, that the tools assessed are only able to pick up broad differences between the GHG emissions from the assessed production scenarios, particularly once those emissions are apportioned by some functional unit. Indeed, there is considerable variation between the estimates produced by the tools, and little or no consistent pattern in terms of the relative magnitude of the emission estimates produced by the different tools, which is no doubt a reflection of the varying approaches taken by them, and because simplifications and/or assumptions are an inevitable element of all carbon calculators (to a greater or lesser extent). Calculators are generally less complex than true GHG emission models, and are intended to inform users without the in-depth scientific understanding required by many models (Whittaker et al., 2013), and as a result, compromises have to be made in favour of system usability. Nevertheless, the extent to which this is done varies considerably. The above tool characterisation process revealed that some tools for example, take into account factors such as animal diet (variations in which may be a key way to control GHG emissions) whilst others make no attempt to do this and rely instead on standard emission factors. Indeed, even for something seemingly as simple as direct energy use (where fuel use amounts are entered, as is the case in all the tools apart from IMPACCT), most models use a single emission factor for use of electricity, whilst others (most notably CCaLC) allow the country in and method by which (i.e. fuel sources - coal, nuclear, renewable) that electricity was generated to be taken into account. It is beyond the scope of this piece of work to comment on which system actually produces the most accurate results (in terms of reflecting real GHG emissions), if indeed any system consistently does so, but it is reasonable to presume that where local conditions and factors can be taken into account, there is a greater likelihood of accurate emission estimates, albeit that they are still estimates.

In light of the above, it would be easy to question the usefulness of such systems when it comes to making sound decisions as to where an individual business should focus its effort in order to reduce GHG emissions (or indeed improve GHG performance more broadly), and adopt a programme aimed at delivering SI. However, in reality this may be more of an issue in relation to the ‘reporting’ function of carbon calculators (Whittaker et al., 2013), in which external groups (regulators, buyers, etc.) wish to make comparisons between producers, particularly in area or production based evaluations.

For example, in order to identify poor performers on a per hectare basis, or to include the better performing producers (per unit of production) within their supply chain. It may be significantly less important when it comes to on-farm management decisions, in which identifying key issues for a particular business to address, is often more important than making comparisons with others.

In relation to this farm management role, the key factor is the ability of the various carbon calculators to perform their awareness raising and mitigation option assessment roles, since SI is most likely to be delivered at a national/international scale, if all businesses are functioning to their best achievable level (e.g. greatest efficiency achievable in their own location). As far as the former is concerned, there can be little doubt that they are all quite capable of identifying the key role played by the livestock themselves in controlling the GHG emissions of dairy enterprises, due to the effects of enteric fermentation (O'Mara, 2011), and that even a small percentage reduction here would be highly beneficial, whereas an equivalent reduction in relation to cropping or (in most cases) direct energy use would be less so. Although clearly if energy use (for example) can be reduced it should be. Identifying key areas in which action could be taken is however, only part of the story, since in order to do so, farmers require true 'decision support' as opposed to 'information provision'. The simplest tools (e.g. CPLANv0) however, provide little or no information of this sort, meaning that although they may be extremely valuable in terms of communicating the scale of the problem and for highlighting the need to act, they may be of less value when it comes to guiding practical farm management decisions and formulating climate change mitigation strategies, as this requires farmers to identify potential mitigation activities and make informed choices between them (Franks & Hadingham, 2012). Fortunately, most tools (e.g. CALM, CCaLC and the COOL Farm Tool) go at least some way towards addressing this issue by apportioning emissions by source and in some cases breaking them down by gas type. In so doing they may highlight particular issues of concern within a production system, allowing further information and solutions to be sought. Others still (IMPACCT and the European Carbon Calculator) go a sizeable step further, and attempt to identify solutions for the user (or at least options they may wish to consider), and in so doing they become considerably more powerful as decision support aids, allowing dairy farmers to make changes to their activities which result in real climate change mitigation benefits, and increases in production efficiency that deliver SI. It is however, no coincidence that the tools which are capable of providing the most advice, are also those with the highest data input requirements, which reflects the fact that to provide genuinely site and business specific advice, a considerable amount of underlying data is required. Users of other systems could of course take advantage of the more generic advice that is available, for instance in the form of internet based best practice guidance; but this may be less likely to steer agricultural decision makers in the most appropriate direction.

Conclusions

The investigations carried out for this study have highlighted a number of issues. Firstly, the GHG emissions of the dairy sector are heavily dependent on the livestock themselves, most notably through enteric fermentation, something which is backed up by the findings of other authors in the field who have pointed to this being the case at the global scale (e.g. O'Mara, 2011). Equally, it is evident that there is considerable variation between the GHG emission estimates produced by different carbon calculators, but that many of the negative issues which might be associated with this, are more likely to be a concern for those trying to make comparisons between farm businesses, than for farm management practitioners trying to identify areas of concern in which improvement is possible. Nevertheless, the extent to which the carbon calculators studied can be said to provide ‘decision support’ varies considerably, with some of the simpler systems being capable of little more than raising awareness of the key issues being faced by the industry. Such systems can however, be easy to use, require very little data entry, and as a result provide an essential entry point for many into the world of GHG emission mitigation. In contrast, those tools capable of providing a good deal of site and enterprise specific advice, are more complex to use, may take significantly longer, have heavy data requirements and/or require a good deal of practice to use them (in the first instance at least). Despite this however, they are more likely to be of practical use in guiding farm management decisions and pushing forward the sustainable intensification of the industry, due to the relatively bespoke nature of the advice given.

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Table 1. Key tool characteristics evaluated.

Characteristic	Description
Stated/implied aim	How tool developers envisage their system being used.
Targeted end users	Farmers, regulators, retailers, etc.
Functional unit	The way in which GHG on-farm GHG emissions are apportioned.
Data needs	How much data input is required?
On-farm data availability	Is additional data collation needed, or is all data likely to be readily available?
Detail of analysis	How much emission estimates are broken down by type / source.
Entry of cattle numbers	Is there any differentiation by age / productivity?
Entry of other livestock	Is there any differentiation by age / productivity?
Cattle feeding / grazing	Is any account taken of livestock diets?
Livestock housing	Does the model differentiate between housed and grazed livestock?
Approach to inorganic fertiliser use	To what degree is N content accounted for?
Approach to organic manure / slurry use	To what degree is type / N content accounted for?
Direct energy use	How is this recorded?
Scope 3 emissions included?	Are emissions resulting from the production of inputs (e.g. fertilisers) accounted for?
Sequestration included?	Is sequestration of atmospheric carbon included in the GHG balance?
Output design, reporting & data storage facilities	What from does the output take and can it be saved for later retrieval?

Table 2. Livestock units (LU) used to apportion greenhouse gas emissions (Redman, 2016).

Animal type	**LU**	**Animal type**	**LU**
Dairy cow	1.00	Other cattle 0-1 years	0.34
Suckler cow	0.80	Other cattle 1-2 years	0.65
Bull	0.65	Other cattle >2 years	0.80

Table 3. Characteristics of assessed carbon accounting tools.

Tool	Source of emission factors/ methodology	Type	Scope	Data requirements	Cattle data type	% grazing in diet assessed?	% housed assessed?	Assesses manure/ slurry N content?	Assesses fertiliser N content?	GHG emission categorised by	Assessments can be saved?
CPLANv0	IPCC tier 1 & national inventory	Online	1 & 2	Light	Type & number	No	No	No	No	Source	No
CALM	IPCC tier 1 & national inventory	Online	1, 2 & some 3	Modest	Number & productivity or age	No	No	Yes	Yes	Source & gas	Online
CCaLC	ISO 14044 & PAS 2050	Application	1, 2 3	High	Liveweight	No	No	No	Yes	Source	Off-line
COOL	IPPC tier 2	Online (ex. Excel)	1, 2 & some 3	High	Number, type & age	Yes	Yes	Yes	Yes	Source & gas	Online (limited in free copy)
IMPACCT	IPCC tier 2 (some 3) & PAS2050	Application	1, 2 & 3	High	Number only	Yes	Yes	Limited	Yes	Source & gas	Off-line
Farm Carbon Calculator	Own	Online	1, 2 & some 3	Moderate	Type & number	Yes	Yes	Partial	Yes	Source	Online (limited No.)
European Carbon Calculator	IPCC tier 2	Excel	1, 2 & 3	Very high	Type, age & number	Yes	Yes	Partial	Yes	Source & gas	Off line

Table 4. Site characteristics of studied farm scenarios.

		Climate		Soil		
Farm	**Country**	**Climatic zone**	**Precipitation (mm yr^{-1})**	**Reference group**	**Dominant surface texture**	**pH**
FR1	France	Warm temperate moist	694	Cambisol	Medium fine silty clay loam	5
FR2	France	Warm temperate dry	618	Luvisol	Medium clay loam	6
FR3	France	Warm temperate moist	694	Cambisol	Medium silt loam	5
IT1	Italy	Warm temperate moist	809	Cambisol	Coarse sandy loam	7
PL1	Poland	Cool temperate dry	566	Luvisol	Medium clay loam	5
UK1	UK	Cool temperate moist	1,053	Gleysol	Medium silty clay loam	4.5

Table 5. Livestock production characteristics of studied farm scenarios.

	Livestock (number)								
	Cows					Heifers			Animals housed (% year)
Farm	**Dairy**	**Pregnant**	**Suckler**	**Dry**	**Bulls**	**Calves / <1 year**	**1-2 year**	**>2 year**	
FR1	100	-	-	-	-	-	36	-	0
FR2	198	-	20	-	1	51	30	41	100
FR3	50	-	-	-	-	-	60	-	25
IT1	340	150	-	50	-	60	200	-	25
PL1	25	-	-	-	-	-	8	-	33
UK1	150	-	-	-	-	93	72	85	50

	Diet (kg DM dairy cow^{-1})								
			Silage			Rolled wheat	Concentrate		
Farm	**Grass**	**Hay**	**Grass**	**Maize**	**Lucerne**		**Triticale**	**Wheat**	**Barley**	**Rapeseed**
FR1	4,406	-	-	680	-	-	474	-	-	-
FR2	-	2,193	793	2,878	-	-	306	-	-	-
FR3	1,617	-	1,551	1,320	-	-	694	207	138	-
IT1	3,123	-	-	215	142	570	-	1,206	402	402
PL1	3,673	-	1,411	-	-	-	-	-	-	-
UK1	1,990	-	2,351	611	-	-	-	1,135.8	378.6	378.6

Table 6. Cropping, milk yield and energy use characteristics of studied farm scenarios (numbers in brackets = number of applications used to achieve total).

	Product	Area (ha)	Yield (t ha^{-1} / L milk)	Fertiliser[a] (kg-N ha^{-1})	FYM[b] (t ha^{-1})	H/F/GR[c] (kg-AI ha^{-1})[d]	Energy use
FR1	Triticale: feed	12.7	4.5	90 (1)	-	1/0.32/0.6	-
	Maize: silage	11	12	50 (1)	-	0.88/0/0	-
	Grass: grazed	104	10	190 (3)	-	0/0/0	-
	Milk	-	460,000	-	-	-	-
Red diesel (L)			-	-	-	-	2,986
Grid electricity (kWh)			-	-	-	-	11,635
FR2	Maize: silage	49	16	35 (1)	25 (1)	0.88/0/0	-
	Triticale: feed	13.5	4.5	72 (1)	30 (1)	1/0.32/0.6	-
	Grass: silage	31.4	11	188 (4)	20 (1)	0/0/0	-
	Grass: hay	112.3	5	58 (1)	20 (1)	0/0/0	-
	Milk	-	1,311,000	-	-	-	-
Red diesel (L)			-	-	-	-	10,088
Grid electricity (kWh)			-	-	-	-	16,619
FR3	Triticale: feed	10	4.5	90 (1)	-	1/0.32/0.6	-
	Grass: 1 cut/ grazed	35	10	294 (3)	50	0.88/0/0	-
	Cereal mix: 60% wheat, 40% barley)	4	6.6	120 (2)	-	1.23/1/1	-
	Maize	14	12	32 (1)	30	0.88/0/0	-
	Milk	-	316,000	-	-	-	-
Red diesel (L)			-	-	-	-	1,347
Grid electricity (kWh)			-	-	-	-	4,410
IT1	Wheat: feed	35	8.6	183 (2)	12 (1)	1.23/1/1	-
	Lucerne: feed	15	5	-	-	1.2/0/0	-
	Maize: silage	8	16	32 (1)	30 (1)	0.88/0/0	-
	Grass: grazed	220	10	334 (1)	10 (1)	0/0/0	-
	Milk	-	2,600,000	-	-	-	-
Red diesel (L)			-	-	-	-	20,943
Grid electricity (kWh)			-	-	-	-	28,963
PL1	Grass: grazed	15	10	187 (2)	5 (1)	0/0/0	-
	Grass: 2 cut	10	7	194 (2)	10 (1)	0/0/0	-
	Milk	-	133,500	-	-	-	-
Red diesel (L)			-	-	-	-	23,159
Grid electricity (kWh)			-	-	-	-	12,024
UK1	Grass: grazed	50	11	194 (4)	10 (1)	0/0/0	-
	Grass: 3 cut	58	12	258 (4)	20 (1)	0/0/0	-
	Maize: silage	17	12	258 (1)	30 (1)	0.88/0/0	-
	Milk	-	1,387,500	-	-	-	-
Red diesel (L)			-	-	-	-	9,547
Grid electricity (kWh)			-	-	-	-	21,652

[a] Fertiliser = NH_4NO_3, [b] FYM = farmyard manure,
[c] H/F/GR = herbicide/fungicide/growth regulator, [d] AI = active ingredient.

Table 7. Summary of the range of total GHG emission estimates produced for six dairy farm scenarios using seven different carbon calculators.

	FR1	**FR2**	**FR3**	**IT1**	**PL1**	**UK1**
Mean	710.77	1,605.69	515.61	3,788.88	241.34	1,802.66
Standard Deviation	145.38	289.67	77.01	826.19	42.79	432.82
Range	379.25	893.96	214.33	2,376.52	103.88	1,319.86
Minimum	506.83	1,198.91	395.89	2,558.60	191.46	1,371.54
Maximum	886.08	2092.87	610.22	4,935.13	295.34	2,691.40
% Difference	53.36%	55.67%	41.57%	62.72%	43.04%	73.22%

Figure 1. Greenhouse gas emission profiles for six farm scenarios - a) total emissions, b) emissions per productive farm hectare, c) emissions per livestock unit, d) emissions per unit of milk production.

Figure 2. Comparative total GHG emission range plots produced for six farm scenarios, broken down into five broad categories of emission source (energy/fuel use, crop residues, livestock, nutrient application, others).

Figure 1

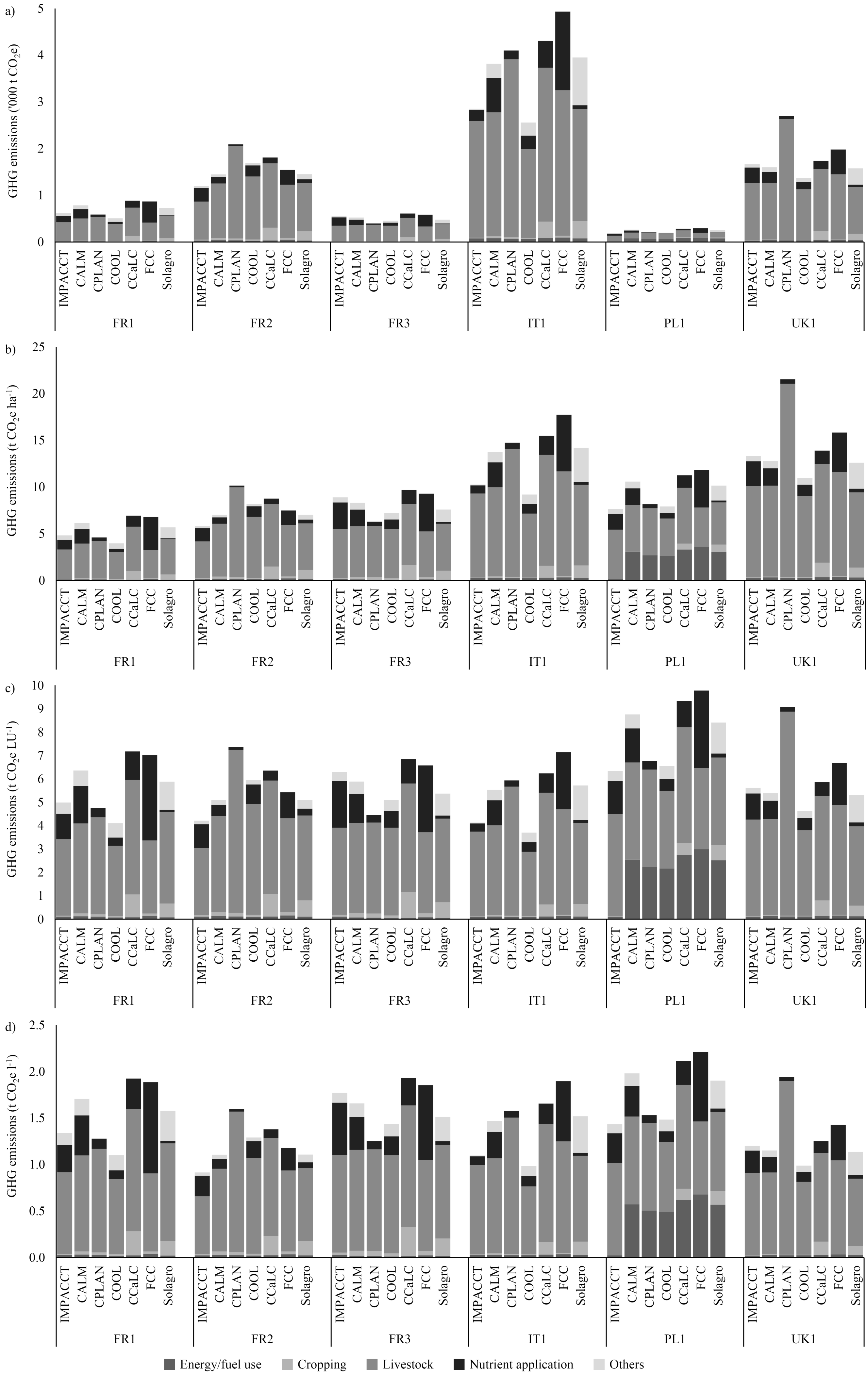
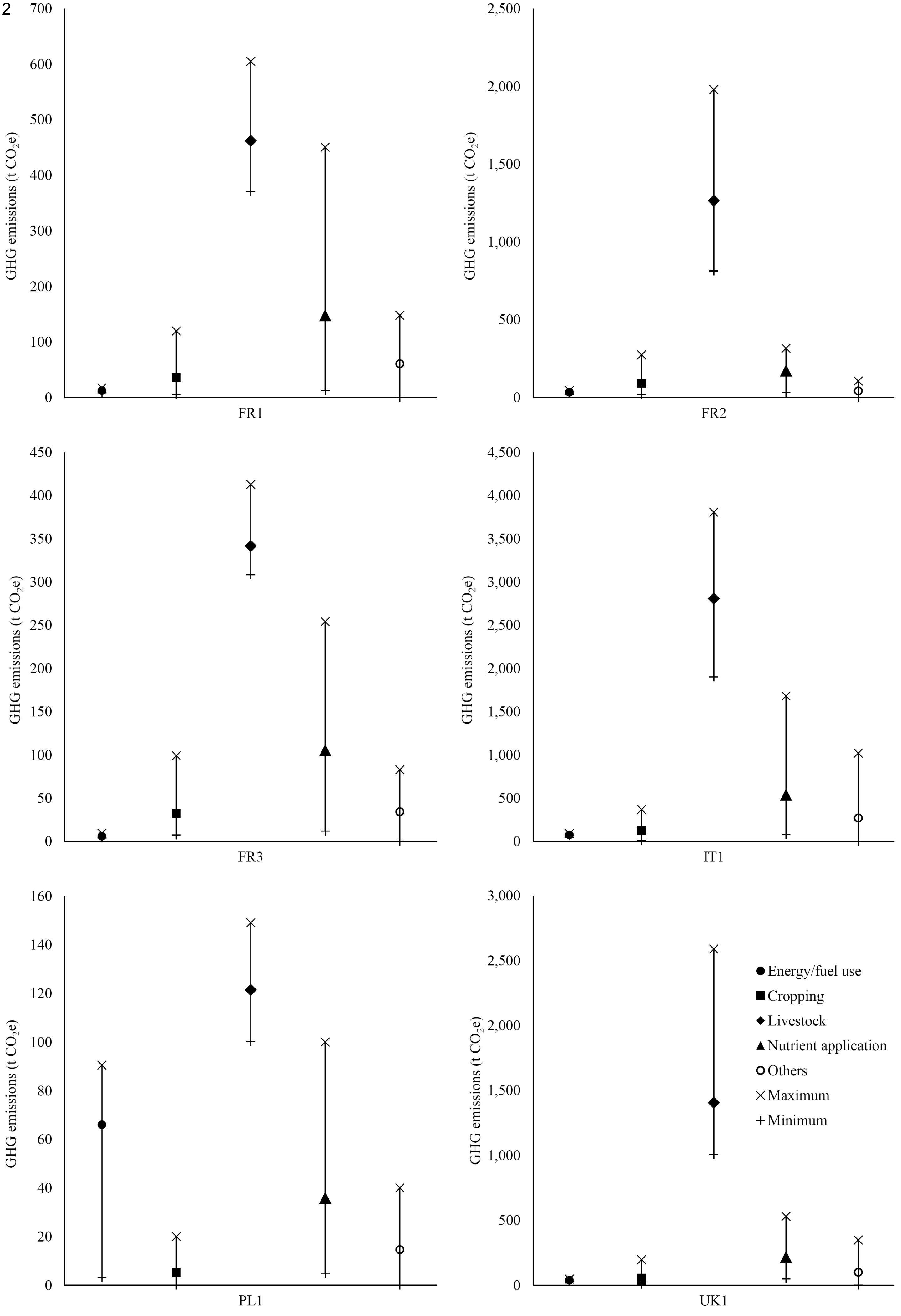

a)
GHG emissions ('000 t CO₂e)
b)
GHG emissions (t CO₂e ha⁻¹)
c)
GHG emissions (t CO₂e LU⁻¹)
d)
GHG emissions (t CO₂e l⁻¹)
IMPACCT
CALM
CPLAN
COOL
CCaLC
FCC
Solagro
FR1
FR2
FR3
IT1
PL1
UK1
Energy/fuel use
Cropping
Livestock
Nutrient application
Others

Figure 2



700
600
500
400
300
200
100
0
GHG emissions (t CO_2e)
FR1
2,500
2,000
1,500
1,000
500
0
GHG emissions (t CO_2e)
FR2
450
400
350
300
250
200
150
100
50
0
GHG emissions (t CO_2e)
FR3
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
GHG emissions (t CO_2e)
IT1
160
140
120
100
80
60
40
20
0
GHG emissions (t CO_2e)
PL1
3,000
2,500
2,000
1,500
1,000
500
0
GHG emissions (t CO_2e)
UK1
Energy/fuel use
Cropping
Livestock
Nutrient application
Others
Maximum
Minimum