

Scotland's Rural College

A comparison of farm-level greenhouse gas calculators in their application on beef production systems

Sykes, AJ; Topp, CFE; Wilson, RM; Reid, G; Rees, RM

Published in:

Journal of Cleaner Production

DOI:

[10.1016/j.jclepro.2017.06.197](https://doi.org/10.1016/j.jclepro.2017.06.197)

Print publication: 15/10/2017

Document Version

Peer reviewed version

[Link to publication](#)

Citation for published version (APA):

Sykes, AJ., Topp, CFE., Wilson, RM., Reid, G., & Rees, RM. (2017). A comparison of farm-level greenhouse gas calculators in their application on beef production systems. *Journal of Cleaner Production*, 164, 398 - 409. <https://doi.org/10.1016/j.jclepro.2017.06.197>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1 **RESEARCH ARTICLE**

2 **A comparison of farm-level greenhouse gas calculators in**
3 **their application on beef production systems**

4
5 Alasdair J. Sykes^a, Cairistiona F. E. Topp^a, Ron M. Wilson^b, Gillian Reid^a, Robert M. Rees^a

6
7 ^aScotland's Rural College (SRUC), West Mains Road, Edinburgh, EH9 3JG, UK

8 ^bThe University of Edinburgh, School of Geosciences, Kings Buildings, West Mains Road, Edinburgh,
9 EH9 3JG, UK

10
11
12 **Corresponding Author**

13 Alasdair J. Sykes

14 Carbon Management Centre, Future Farming Systems Group, Scotland's Rural College (SRUC)

15 West Mains Road, Edinburgh, EH9 3JG, UK

16 Email: alasdair.sykes@sruc.ac.uk

17 Tel: 0131 535 4383

18
19 **Word count** (including headings, captions, and tables; excluding abstract, acknowledgements and
20 references):

21 **8,304**

28 **Abstract**

29 Farm-level greenhouse gas (GHG) footprinting tools produce markedly different results from common
30 input datasets. These tools are typically empirical, broad scope models which are valuable for their ability
31 to account for a range of on-farm GHG sources using non-specialist data. Many of these tools are publicly
32 available, and are employed by users from a range of backgrounds to provide enterprise-level carbon
33 footprints. They may be used to inform mitigation strategies and policy developments, though are often
34 developed outside the peer-review system, and as such the methodology employed may be sparsely
35 documented.

36 The study reported here rigorously tests these tools and discusses differential findings. Five farm-
37 level tools were tested using data from a variety of beef production enterprises. Beef production was
38 chosen as an emissions intensive form of livestock production, and the focus of considerable mitigation
39 effort globally. Considerable inconsistencies between tools were found in the resulting estimates.

40 Estimates of emissions stemming directly from livestock were variable, and the largest contributor
41 to the overall farm footprint (43 – 92% of total). As such, consistent calculation of these emissions is of
42 considerable importance. Similar variability was found in other emissions categories. The emissions
43 intensity of beef production was calculated for each estimate and compared to published values from LCA
44 literature. Some tools produced estimates concurrent with these values, whilst others markedly
45 underestimated in comparison.

46 This study highlights the differences between estimates produced by these tools, and explores the
47 reasons behind them. Of relevance to users is the finding that even where farm-level estimates appear
48 similar between tools, the composition of these estimates can vary. As such, different tools respond
49 differently to system changes. In highlighting and exploring the impacts this can have, the conclusions of
50 this study provide a key reference point for tool users and developers.

51

52

53 **Keywords:** carbon calculator, carbon footprint, farming systems, beef production, livestock, greenhouse
54 gas

55

56 **1. Introduction and rationale**

57 Agriculture in the UK was responsible for the emission of 48 Mt CO₂-eq in 2008, a contribution of 8% to
58 national emissions (Committee on Climate Change, 2010). Under the Climate Change Act 2008, the UK
59 Government is committed to reducing national emissions to 20% of 1990 levels by 2050; UK agriculture is
60 correspondingly required to achieve a 34% reduction by 2020 (Committee on Climate Change, 2008). This
61 commitment in the UK follows international climate commitments; the EU Roadmap recommends a
62 reduction in European agricultural emissions of 36-37% for 2030, and 42-49% for 2050 (Domingo et al.,
63 2014).

64 Moran et al. (2011) show that to achieve this target will require considerable mitigation effort
65 within the agricultural sector. The livestock sector contributes substantially to agricultural emissions and
66 hence is likely to come under detailed scrutiny. Quantifying and mitigating for GHG emissions from
67 livestock is therefore of considerable policy importance on both national and international scales. Whilst
68 quantification of farm-level emissions is not straightforward, it is a crucial step towards cleaner
69 agricultural production (Yan et al., 2015).

70 A number of tools, developed in a variety of contexts, are available to assist with this process
71 (Colomb et al., 2012). By providing a quantitative assessment of farm-level emissions, these tools perform
72 a crucial role in facilitating reduction in the environmental impact of production. Some, such as the Cool
73 Farm Tool (Hillier et al., 2011) have been developed within the academic sector; others such as CPLANv0
74 (SEE360, 2007) have been developed by businesses for consultancy-oriented purposes. Others, such as the
75 CALM tool (CLA, 2009) are developed by not-for-profit organisations.

76 Hall et al. (2010) reviewed three UK-specific farm GHG accounting tools with the aim of
77 recommending a single tool for promotion by the Scottish Government. However, the authors found that a
78 qualitative approach was insufficient to recommend a single tool for this purpose. A lack of consensus in
79 GHG accounting methods, together with lack of available information on tools was a key reason for this
80 conclusion.

81 Without this consensus in place, each tool employs a unique range of methodologies, and the
82 scope of assessment varies. This may be the product of the context in which a tool was developed; Colomb
83 et al. (2012) note that this factor is likely to affect the depth and scope of a tool. Furthermore, the
84 requirement to combine methodologies, inherent in the nature of such broad-scope models, is likely to

85 further exacerbate differences. Some methodologies, such as the IPCC (2006) Guidelines, were not
86 specifically intended for farm-level calculations, and so the necessary adaptation of these may act as
87 further basis for disparity. Whittaker et al. (2013) found that tool transparency is often insufficient to shed
88 light on the decisions made whilst adapting these methodologies.

89 In order to gain further insight into these issues, several studies have included quantitative
90 analyses of these tools. These studies test tools in the context of the cultivation of palm oil and sugar cane
91 (Keller et al., 2014), wheat in the United Kingdom (Whittaker et al., 2013), and a variety of European
92 cereal cultivation scenarios (Lewis et al., 2013). All highlight disparities between tools in terms of scope,
93 boundaries, and results. However, whilst illuminating in many respects, these studies have been limited in
94 that all concern only arable enterprises. Given the contribution of livestock to agricultural emissions both
95 in the United Kingdom (Moran et al., 2011) and further afield (Xu and Lan, 2016), coupled with the
96 relative complexity of livestock systems (Schils et al., 2007) and the recognised issues with many available
97 tools, the requirement for an empirical assessment of these tools on representative livestock enterprises is
98 increasingly apparent.

99 This study aims to provide a reference point for prospective tool users in selecting a tool for their
100 purposes, and for developers in further improving the tools. Tools of this type have proven potential in
101 facilitating environmentally efficient agricultural production (e.g. Hillier et al., 2011), but the evidenced
102 methodological variation and lack of accompanying information for many tools (Whittaker et al., 2013)
103 means that users require further insight in order to realise this potential. Such an assessment must follow a
104 critical, quantitative approach in order to provide maximum insight, and this study seeks to fulfil that
105 requirement through a quantitative comparison of tool estimates based on a representative range of UK
106 livestock enterprises. The relevance of such an approach is heightened by the importance of livestock
107 production in both agricultural and national-level GHG budgets. Robust conclusions are sought as to the
108 consequences of existing differences in accounting methods on the final farm-level footprint, and on
109 corresponding implications for users and policy makers.

110

111

112

113 **2. Methodology**

114

115 **2.1. Calculator selection**

116 Farm-level carbon accounting tools were selected for review based on pre-determined criteria, defined as
117 follows:

118 Tools had to be greenhouse gas calculators applicable to the livestock industry and specific to the
119 agricultural sector. Data constraints (Section 2.3) meant that tools had to be, if not UK-specific, at least UK
120 applicable. Additionally, it was determined that tools must be publicly available without cost, and must
121 function at farm-level.

122 Tools were sourced via web searches and from previously completed reviews, specifically
123 Colomb et al. (2012) and Whittaker et al. (2013). Five tools were identified as complying with the above
124 criteria and were selected for review (Table 1). These are described below. No suitable tools were
125 knowingly rejected from the sample. Table 2 provides a summary of tools' scope and system boundaries.

126

127 **Table 1.** Farm-level GHG accounting tools chosen for review.

Name	Developer	Type	Website
AgRE Calc	SAC Consulting	Online	www.agrecalc.com
Cool Farm Tool	Cool Farm Alliance Country Land & Business Association (CLA)	Online/Excel download	www.coolfarmtool.org
CALM	Business Association (CLA)	Online	www.calm.cla.org.uk
CPLANv0	See360 Ltd.	Online	www2.cplan.org.uk
CFF Calculator	Climate Friendly Food	Online	www.cffcboncalculator.org.uk

128 *2.1.1. AgRE Calc*

129 AgRE Calc (SRUC, 2014), standing for Agricultural Resource Efficiency Calculator, was developed by
130 the consulting division of Scotland's Rural College. The tool forms part of the organisation's consultancy
131 services, though is freely available for non-commercial use.

132 IPCC (2006) Tier II calculations are employed to calculate livestock and manure management
133 emissions. Emissions from production of fertilisers and pesticides ('embedded' emissions) are calculated
134 using Carbon Trust (2010) emission factors, whilst N₂O emissions from fertiliser and crop residues follow
135 IPCC (2006) Tier I methodology. The tool also calculates embedded emissions for imported feed and
136 bedding, based on emission factors (EFs) from Kool et al. (2012).

137 Electricity, renewable energy and fossil fuel emissions are calculated using emission factors from
138 DEFRA/DECC (2011) Conversion Factors for Company Reporting. Finally, carbon sequestration from
139 woodland is calculated using IPCC (2006) methodology at Tier I level. The online tool is certified under
140 the PAS2050:2011 specification for GHG life cycle assessment (BSI, 2011).

141 *2.1.2. The Cool Farm Tool*

142 The Cool Farm Tool (Hillier et al., 2011) was developed at the University of Aberdeen and is freely
143 available under a creative commons licence. Hillier et al. (2011) state that the tool was designed to
144 function at an intermediate level; requirement for high levels of data input was avoided, but provision for
145 data input beyond the standard Tier I inventory methods (IPCC 2006) were included, providing insight on
146 a local scale. The tool is unique in this sample in that the methodology has been published in peer-
147 reviewed literature (Hillier et al., 2011) where the development of the Cool Farm Tool is described. The
148 EcoInvent emission factor inventory (Ecoinvent Centre, 2007) was used to provide EFs for fertiliser
149 production and renewable electricity usage. Hillier et al. (2011) incorporated a model developed by
150 Bouwman et al. (2002) to determine N₂O emissions relating to fertiliser usage. IPCC (2006) methodology
151 was used for livestock and manure emissions. Hillier et al. (2011) state that the model can perform Tier I
152 or Tier II level calculations, as allowed by input data. The tool is not PAS2050 certified, though has been
153 extensively reviewed in academic and non-academic literature.

154

155

156 *2.1.3. The CALM Calculator*

157 The CALM Carbon Calculator was developed by the Country Land and Business Association, in
158 partnership with Savills (CLA 2009). The model methodology is described as following that used in the
159 most recent National Inventory Report.

160 Model methodology assesses N₂O emissions from crop residues, fertiliser and manure
161 management. Methane emissions from enteric fermentation and manure management are calculated.
162 Embedded emissions from synthetic fertiliser and lime are assessed, as are emissions associated with on-
163 farm fuel and electricity use. The model can also assess sequestration from forestry, soil organic carbon
164 and land use change. Embedded emissions associated with purchased feed and bedding are not assessed.
165 The tool appears to draw on methodology from the IPCC Guidelines for emissions from livestock and
166 manure (Dong et al., 2006) and land management (de Klein et al., 2006), and the UK GHG inventory
167 (DEFRA/DECC, 2013), though is not PAS2050 certified.

168 *2.1.4 – CPLANv0 Calculator*

169 CPLANv0 (SEE360 2007) is a free-to-use carbon calculator which forms part of a consultancy business.
170 The development was supported by public funding. The model forms a key component of the agricultural
171 consultancy business SEE360 Ltd.

172 CPLANv0 forms the basis for CPLANv2, a more detailed calculator which is not free to use.
173 Other than the statement that IPCC (2006) methodology has been observed, there is little detail given as to
174 the methodology of the CPLANv0 calculator. The system boundaries include CH₄ from enteric
175 fermentation and manure. Nitrous oxide from crop residues and fertiliser is assessed. Emissions from fossil
176 fuel and electricity use are also included. The sequestration potential of standing woodland is assessed, as
177 well as impacts from forestry and land use change. The tool is not PAS2050 certified.

178 *2.1.5 – CFF Carbon Calculator*

179 The Farm Carbon Calculator (CFF Carbon Calculator, 2012) is a not-for profit online tool which places a
180 strong emphasis on organic agriculture. The livestock section of the model appears to be based on standard
181 Tier I methodology (IPCC, 2006), though this is not specifically stated.

182 The model has the capability to assess GHG emissions from fuel and electricity use, material
183 consumption, crop production/importation, fertiliser use, enteric fermentation and manure management.

184 There is the facility to assess emissions associated with building materials and capital items such as farm
 185 machinery. There are functions to assess post farm gate haulage emissions, and to assess carbon
 186 sequestration by woodland, orchards, hedges and field margins.

187 Little emphasis is placed upon N₂O emissions (Whittaker et al., 2013). Where these are associated
 188 with crop residues, they are considered in the model; however, the calculations take no account of N₂O
 189 emissions from fertiliser spread or from manure. The tool as a whole does not hold PAS2050 certification.

190 **Table 2.** Summary of emissions sources included by the tools. Note that this table is not intended as an exhaustive list of
 191 farm-level emissions sources, but is tailored to the tools and input data. *Y* = included, *N* = not included, *?* = unclear.

		AgRE Calc	Cool Farm Tool	CALM	CPLAN v0	CFF
Crop residues	N₂O	Y	Y	Y	Y	Y
Manure application	N₂O	Y	Y	Y	Y	N
Fertiliser application	N₂O	Y	Y	Y	Y	N
Lime/urea application	CO₂	Y	Y	Y	Y	N
Manure management	CH₄	Y	Y	Y	Y	Y
	N₂O	Y	Y	Y	Y	N
Enteric fermentation	CH₄	Y	Y	Y	Y	Y
Fertiliser	(embedded)	Y	Y	Y	?	Y
Feed	(embedded)	Y	Y	N	N	Y
Bedding	(embedded)	Y	Y	N	N	N
Pesticides	(embedded)	Y	Y	N	N	Y
Plastics	(embedded)	Y	N	N	N	Y
Diesel	CO₂	Y	Y	Y	Y	Y
Electricity	CO₂	Y	Y	Y	Y	Y

Woodland (sequestration)	CO₂	Y	Y	Y	Y	Y
-------------------------------------	-----------------------	---	---	---	---	---

192

193 ***2.2. Data acquisition***

194 Sample data for seven farms was sourced from within the repository of Scotland’s Rural College (SRUC);
 195 these represented a mix of SRUC-owned farms and independent affiliated enterprises from different
 196 regions across Scotland. In selection, emphasis was placed on beef production; this in part reflects the high
 197 environmental impact of beef as compared to other livestock enterprises (Eshel et al., 2014), and provides
 198 a link between each of the farms for comparison of emissions intensity.

199 The farms nevertheless contained a mix of additional enterprises, and are summarised below, with
 200 Table 3 presenting the standing herds and output from each enterprise.

201 **Farm A** comprised of a total of 1,015 ha, with 939 ha a mix of hill, upland and lowland grazing.
 202 Arable crop production on the remainder partially supplied the feed requirements of the livestock. The
 203 farm ran cattle in a breeder/store system with 200 suckler cows, and a mixed hill and lowland sheep system
 204 with 1,200 ewes.

205 **Farm B** produced winter wheat, winter barley, spring barley and oats on 242 hectares of land. An
 206 additional 282 hectares were under grass to support the beef enterprise, which comprised a herd of 300
 207 Limousin cross suckler cows, with all progeny finished on the farm.

208 **Farm C** had a large dairy herd with around 250 milking cows. A smaller beef enterprise drew on
 209 the dairy herd, and a flock of 312 ewes produced 500 lambs for sale annually.

210 **Farm D** comprised a suckler beef unit of 100 cows, and a sheep unit of around 300 ewes which
 211 produced around 500 lambs for sale annually. A large pig unit of comprising approximately 650 adults and
 212 2,000 juveniles was also present. Around 92 hectares of crops were grown to support the livestock
 213 enterprises.

214 **Farm E** was an upland beef and sheep farm, comprising a beef herd with 140 suckler cows, and
 215 two sheep flocks comprising 800 ewes in total. Around 8 hectares of land was used to grow forage crops to
 216 support the livestock enterprises.

217 **Farm F** was a 329 hectare organic dairy farm comprising a herd of 170 dairy cows. The business
 218 retained all of the offspring from the dairy herd, and finished around 100 head of cattle for beef annually.
 219 Additionally, 56 hectares of land was devoted to arable production, supporting the livestock enterprises.

220 **Farm G** comprised a flock of around 250 Dorset cross ewes, 30 mixed breed suckler cows and a
 221 varying number of finishing cattle bought as stores or weaned dairy calves from other organic units.
 222 Around 20 hectares of cereals were grown to provide winter feed for the livestock. Livestock were finished
 223 on farm.

224 Carbon footprinting data characterising these farms was collected by SAC Consulting for calendar
 225 year 2014, except for farms E and F, where data availability necessitated the use of 2013 data. Boundaries
 226 for system characterisation were cradle to farm gate (see Section 2.3 for further details).

227

228 **Table 3.** Annual herds, land areas and outputs for farms A – G, based on the sample data. The values given in head (Hd)
 229 refer to the average number over the footprint year, and hence reflect a) the individual year in question, and b) the proportion
 230 of the year spent on the system by each livestock category.

			Farm A	Farm B	Farm C	Farm D	Farm E	Farm F	Farm G
Beef Cattle	Cows		266	274	8	100	146		28
	Bulls		5	7	1	4	6		1
	Heifers	Hd	116	213	17	133	108	64	48
	Steers/Male entire ¹		222	199	22	63	57	143	79
Sheep	Rams		42		26	10	34		12
	Ewes	Hd	1,203		312	310	783		265
	Juvenile		948		94	168	600		40
	Lambs		900		240	294	644		300
Dairy Cattle	Cows				257			173	
	Bulls				1			2	
	Heifers	Hd			149			139	
	Steers				38				
Pigs	Adult				659				
	Juvenile	Hd			2,080				
Land	Rough Grassland		622	7.3		24.1	788	35.1	128.2
	Improved Grassland	Ha	314	173.3	194.2	145.8	188	184.6	78.4
	Arable		49.7	243.3	54.6	91.9	8	55.9	19.8
	Woodland		11.8		16.2	30.1	33.3	51.4	80.8
Sales	Beef Suckler Cows	kg	17,342	34,104	1,300	7,700	12,826		
	Beef Bulls	LW	1,500			1,250	1,044		

Beef Heifers		77,803	49,579	1,500	20,376	19,494	39,078	9,680
Beef Steers		77,803	69,687	3,120	24,050	27,813	29,880	26,000
Beef Male Entire ¹		3,960	21,000					
Ewes		19,800		1,440	3,975	18,200		3,740
Rams	kg LW	425		0		300		255
Lambs		41,589		23,000	24,940	55,440		10,955
Dairy Cows				3,404			18,690	
Dairy Bulls	kg LW			650			565	
Dairy Male Entire ¹				118,750				
Sows					2,322			
Boars	kg LW				230			
Finishing Pigs					814,200			
Wool	t	4.72		0.83	0.71	3.19		0.78
Milk				1,978			1,315	
Barley			921					
Oats			86					
Wheat	t		461		524			
Oilseed Rape					56			

231 ¹The male entire categories refer to uncastrated juvenile male dairy/beef cattle.

232

233 **2.3. Data Preparation and Processing**

234 The following data categories were supplied for each farm by the raw datasets:

- 235 • Land use category and area
- 236 • Arable yields by crop type
- 237 • Fertiliser and pesticide usage, type and application rates
- 238 • Livestock age, class and performance data
- 239 • Livestock feed types, quantities and provenance
- 240 • Manure management system types and usage
- 241 • On farm electricity and fuel use (at enterprise level)

242 To provide a baseline for comparison of outputs from the different models, manual estimates were
243 calculated for emissions stemming directly from livestock (CH₄ enteric fermentation and N₂O manure
244 deposition and management). This was done according to Tier I and II level methodology as specified in
245 the IPCC (2006) Guidelines.

246 Summarising the approach, Tier I manual calculations used default emission factors for Western
247 Europe for emissions from both enteric fermentation and manure. By contrast, the Tier II calculations
248 followed the energy-based calculations as stipulated by the Guidelines, and made use of all activity data

249 present in the sample datasets. Additionally, an online database resource, Feedipedia (INRA, 2012) was
250 used to provide data for calculating the digestible energy and crude protein in the diet (DE% and CP%) at
251 enterprise level, a required input for Tier II level calculation.

252 An emissions intensity estimate, in kg CO₂-eq / kg beef Live Weight (LW), was derived from the
253 farm level results. In order to calculate this, it was necessary to allocate the emissions which formed the
254 whole-farm estimate to different enterprises on the farms. However, with the exception of AgRE Calc,
255 none of the sampled tools allocate emissions within the farm footprint.

256 AgRE Calc contains integrated protocols for the allocation of emissions to the end user enterprise
257 wherever resource transfer (such as the provision of home-grown feed to livestock) occurs on farm. In the
258 case of co-production (such as cereal grain and straw), allocation of emissions to products is based on
259 economic value. For AgRE Calc, emissions as calculated for the beef enterprise were utilised. For
260 estimates from other tools, in the absence of an integrated approach, the enterprise allocations as calculated
261 by AgRE Calc were applied as a ratio through which gross emissions estimates were processed. To derive
262 the emissions intensity, the annual beef enterprise footprint was divided by the beef LW sales, providing
263 an emissions intensity estimate in kg CO₂-eq / kg beef LW.

264
265

266 **3. Results and Discussion**

267

268 ***3.1. Whole-Farm GHG Emissions***

269 A total of 35 emissions estimates were calculated from the seven datasets and five tools. The data allowed
270 complete footprints to be produced from each tool, with two partial exceptions, Firstly, CPLANv0 did not
271 include embedded emissions estimates for any sources (Section 3.3.2). Secondly, the Cool Farm Tool
272 required more detail than was available in the sample data in order to produce an estimate for woodland
273 CO₂ sequestration (Section 3.3.4). Including CO₂ sequestration by woodland, results ranged from -6.67
274 (CALM Tool, Farm G) to 3.89 kt CO₂-eq y⁻¹ (AgRE Calc, Farm A). Excluding sequestration, these totals
275 ranged from 0.15 (CPLANv0, Farm G) to 4.02 (AgRE Calc, Farm A). Whilst this represents, to some

276 extent, the actual variability in farms, a considerable amount is attributable to the tools themselves, and it
 277 is therefore notable that the range of estimated emissions between farms using the same calculator is
 278 comparable with the range of emissions on an individual farm using different calculators (Table 4).

279

280 **Table 4.** Gross farm-level GHG footprints (in kt CO₂-eq y⁻¹) as calculated by the five sample tools. Sequestration of CO₂ by
 281 woodland (negative) is not included in these totals.

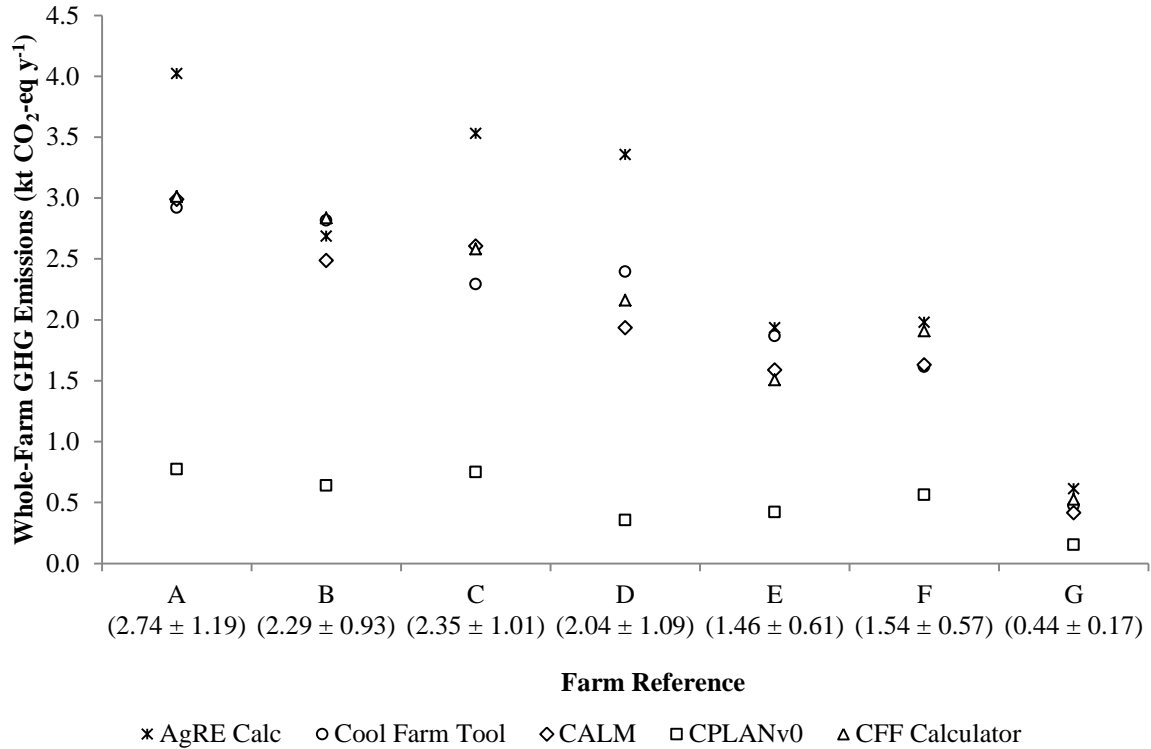
282

Farm	AgRE Calc	Cool Farm Tool	CALM	CPLANv0	CFF Calculator	Mean	Range
A	4.02	2.92	2.99	0.77	3.01	2.74	3.25
B	2.69	2.82	2.49	0.64	2.84	2.29	2.2
C	3.53	2.29	2.61	0.75	2.58	2.35	2.78
D	3.36	2.4	1.94	0.35	2.16	2.04	3
E	1.93	1.87	1.59	0.42	1.51	1.46	1.51
F	1.98	1.61	1.63	0.56	1.91	1.54	1.42
G	0.61	0.47	0.42	0.15	0.53	0.44	0.46
Mean	2.59	2.05	1.95	0.52	2.08		
Range	3.41	2.45	2.57	0.62	2.48		

283

284 Even with results fully aggregated, it is apparent that some tools are following markedly different
 285 approaches to the process of farm-level GHG accounting (Fig. 1). The CPLANv0 tool appears consistently
 286 below the general trend. AgRE Calc produced the highest results on average. A partial grouping is
 287 apparent, with results from CALM, the Cool Farm Tool, the CFF calculator and, to some extent, AgRE
 288 Calc, following a similar pattern.

289



290

291 **Figure 1.** Total GHG footprints for each of the five calculators over the seven sample farms. Sequestration of CO₂ by
 292 woodland, deductible from the footprint, is excluded from the totals in this figure. The calculated mean estimate from the
 293 five tools ± 1 *S.D.* are shown in parentheses.

294 Tool variability was reasonably consistent relative to the magnitude of the estimate. Estimates for Farm D
 295 were somewhat more variable, however; a large pig enterprise dominates output for this farm (Table 3),
 296 implying higher levels of inconsistency in the way that emissions were calculated for this livestock type.

297 Between 5 and 14 (*Mdn* = 10, *N* = 35) individual sources made up the total emissions estimate for
 298 each farm. This highlights an issue inherent in farm-level footprinting; with every additional emission
 299 source included in the estimate, the number of potential causes for methodological variability in the final
 300 footprint increases accordingly.

301 As such, it is entirely possible for the composition of estimates to differ without affecting the final
 302 value of the farm-level footprint. The insight which can be gained by examining the footprints at farm-
 303 level is therefore limited, and to further explore the model methodology, the following sections examine
 304 these estimates at category level.

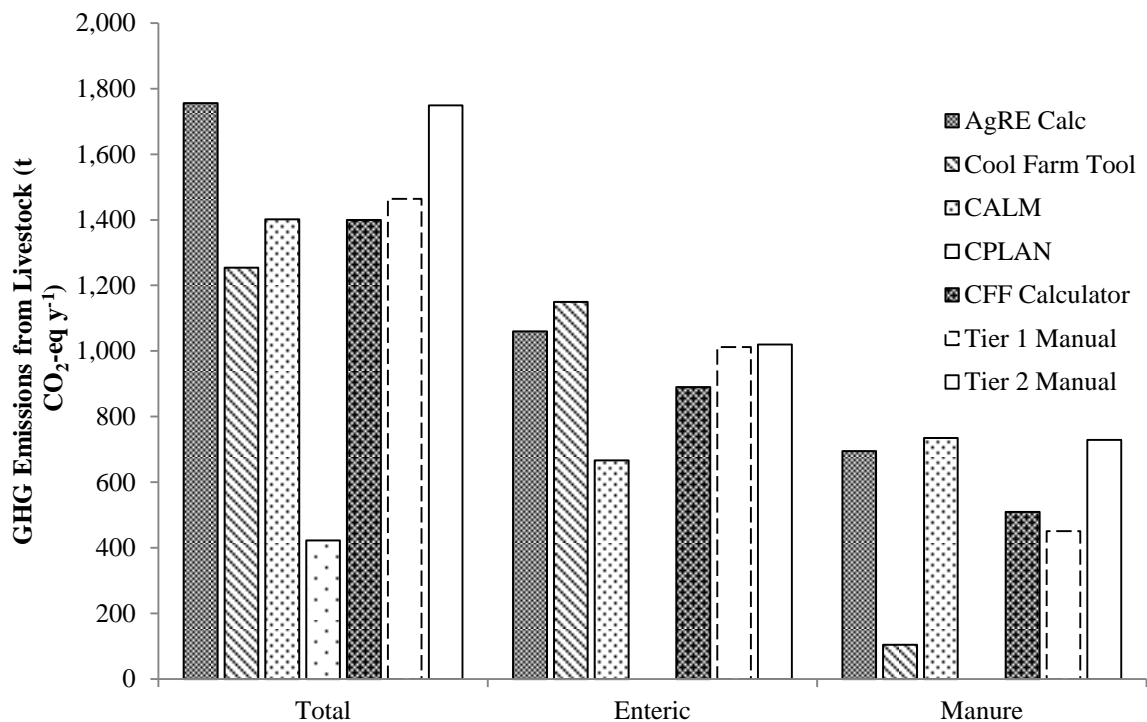
305

306

307 **3.2. Livestock Emissions**

308 Direct emissions from livestock represented the largest overall emissions category, contributing between
 309 43% and 92% ($M = 72\%$, $N = 35$) to the overall farm-level footprint. As such, emissions from this source
 310 are broken down into the two contributing subcategories (enteric and manure emissions) for analysis.
 311 Included in this assessment were estimates from all five tools, as well as manually calculated Tier I and II
 312 estimates (Fig. 2).

313



314

315 **Figure 2.** Graph showing mean livestock emissions estimates ($n = 7$) for each of the tools and manual calculations, including
 316 a breakdown into subcategories. The CPLANv0 calculator did not produce results at subcategory level and hence only the
 317 total is shown for this tool.

318 The Tier I and II manual calculations show consistent disparity across the sample farms. Tier I
 319 methodology gave lower total livestock emissions as compared to Tier II level calculations for the farms
 320 included in this study (Fig. 2). Further examination of results indicated that manually calculated Tier I
 321 estimates ranged from 74.7% – 98.6% of their Tier II counterparts ($M = 84.5\%$, $N = 7$).

322

Examining the breakdown of these emissions into subcategories, it is clear that the difference
 323 between the Tier I and II methodology stems from the estimate of manure emissions (Fig. 2). One
 324 explanation for this lies in the fact that Tier I methodology employs activity data for manure management

325 system usage which is generic to Western Europe. Manure management systems vary considerably, and so
326 if this data does not accurately represent the sample farms, it could lead to the disparities shown here.

327 *3.2.1. AgRE Calc*

328 A close grouping can be observed between AgRE Calc and the manual Tier II calculations. For manure
329 calculations, AgRE Calc differs from the manual Tier II approach in that it uses expert-supplied reference
330 data to calculate the N content of manure (SRUC, 2014); this factor directly impacts N₂O emissions and
331 can affect the total emissions substantially. This approach reduces data demand, an important consideration
332 for farm-level tools. The close match to Tier II, for which N content was manually calculated, suggests that
333 this is one area in which data demand may be reduced without unduly impacting results, though doing so
334 limits the flexibility of the estimate.

335 *3.2.2. The Cool Farm Tool*

336 Hillier et al. (2011) followed IPCC (2006) Guidelines for the calculation of livestock emissions within the
337 Cool Farm Tool, which is stated to perform at either a Tier I or Tier II level depending upon the
338 availability of data. Sample data for all farms was sufficient to perform a Tier II estimate. Overall,
339 however, results from the Cool Farm Tool undervalue livestock emissions as compared to the average
340 totals for both Tiers of calculation (Fig. 2). This difference stems from the estimate for manure emissions.
341 The Cool Farm Tool underestimates manure-related emissions as compared to both methodological Tiers,
342 and to other tools. The reasons for this are unclear; given the methodological description by Hillier et al.
343 (2011), the estimates would be expected to lie close to the Tier II manual estimates.

344 The relative contributions from subcategories to the livestock total are, for this tool, in stark
345 contrast to other methodologies; at the livestock category and whole farm level, however, the Cool Farm
346 Tool does not differ substantially (Figs. 1 and 2). Whilst the total result is unaffected, this means that the
347 Cool Farm Tool would be likely to respond differently to changes in the livestock system, as compared to
348 other tools.

349 *3.2.3. The CALM Tool*

350 Total livestock emissions as estimated by the CALM tool are similar to the manual Tier I calculations (Fig.
351 2). However, further breakdown reveals that the CALM Tool underestimated enteric emissions as

352 compared to both Tiers. By contrast, the CALM tool's estimate of manure emissions was similar to Tier II.
353 One possible explanation for this is that the CALM tool, though using a Tier I emission factor, calculates
354 emissions based on farm-specific activity data. This may have captured some variability in manure
355 emissions missed by the manual Tier I approach.

356 The CALM Tool was the only model to estimate, on average, higher manure-related emissions as
357 compared to enteric emissions, apparently through underestimation of the latter. While methodology
358 behind this is unclear, the response of the CALM calculator to livestock system changes would likely
359 differ to other tools for this reason.

360 *3.2.4. CPLANv0*

361 Total emissions as estimated by the CPLANv0 calculator fell starkly below those of all other tools and
362 both manual calculations (Fig. 2). This result is striking given the statement by the tool developers that
363 the CPLANv0 tool follows IPCC (2006) methodology throughout (SEE360, 2007). The CPLANv0 tool
364 presented results in highly aggregated format, and as such it was not possible to derive a breakdown for the
365 livestock emissions category, hindering further speculation as to the methodology employed.

366 *3.2.5. The CFF Calculator*

367 The CFF calculator produced an average total emissions estimate which did not differ greatly from the Tier
368 I methodology. Further examination of the breakdown of this estimate would suggest that the methodology
369 closely mirrors the approach taken by the manual Tier I calculation.

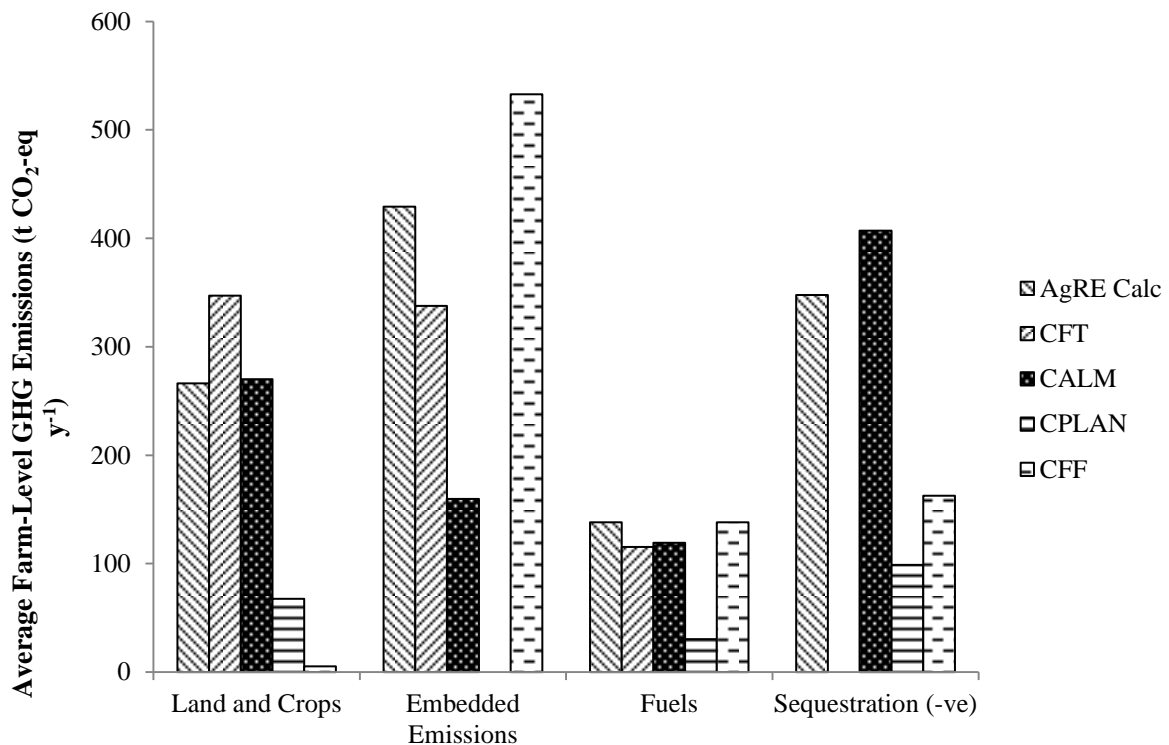
370 The CFF Calculator produced results for manure which did not differ substantially from the Tier I
371 manual calculation. This is surprising in that Whittaker et al. (2013) state that the only source of N₂O
372 included by the CFF tool is crop residues, implying that N₂O is neglected in the estimate of manure
373 emissions. It is difficult to confirm this explanation, as the tool does not provide results disaggregated by
374 gas. It is plausible that an update has taken place since the study by Whittaker et al. (2013). Lack of
375 methodological transparency such as this makes it difficult to predict how a tool will react to system
376 changes.

377

378 *3.3. Emissions from Other Sources*

379 Emissions from sources other than livestock were assessed in the following categories, defined as 1) Land
 380 and Crops, 2) Embedded Emissions, 3) Fuels, and 4) Sequestration. Note that the fuels category includes
 381 emissions from electricity production and fossil fuel extraction, in addition to direct emissions. The
 382 average estimates for these categories are presented graphically in Fig. 3.

383



384

385 **Figure 3.** Average emissions for the seven sample farms, disaggregated by source category, as calculated by each tool.

386 3.3.1. Land and Crops

387 Emissions estimates were found to be highly variable for the Land and Crops category. In contrast to the
 388 low result produced by the Cool Farm Tool for manure emissions, the emissions estimate from land and
 389 crops exceeded that of all other calculators ($m = 347,224 \text{ kg CO}_2\text{-eq y}^{-1}$). In comparison to the Tier I
 390 methodology employed by AgRE Calc and the CALM tool, the Bouwman et al. (2002) model employed
 391 by the Cool Farm Tool appears to have predicted slightly higher emissions than the IPCC methodology.
 392 Whilst the reasons for this are unclear, the Bouwman model captures greater variability in soil conditions
 393 than the Tier I approach, which may explain the difference in emissions.

394 Markedly lower than the general grouping were estimates by CPLANv0 and the CFF Calculator.

395 For CFF Calculator, this difference is explicable, as the tool excludes all sources of N₂O emission with the

396 exception of crop residues (Whittaker et al., 2013). This omission is substantial, with the mean land and
397 crop estimate from the CFF Calculator ($m = 5.19 \text{ t CO}_2\text{-eq y}^{-1}$) only 2.7% of the value of the mean estimate
398 across all other tools ($m = 191.24 \text{ t CO}_2\text{-eq y}^{-1}$).

399 The CFF Calculator estimates embedded emissions at a level much higher than the general
400 grouping. It is possible that some of the ‘missed’ N₂O emissions are incorporated into this category,
401 though without further methodological information or disaggregation of results it is not possible to confirm
402 this speculation.

403 These omissions are likely to affect how the CFF Calculator responds to mitigation options
404 designed to reduce N₂O emissions from land and crops. Optimisation of fertiliser application (and
405 avoidance of over-applying) has been found to be a viable and cost-effective mitigation measure (Domingo
406 et al., 2014); through excluding of this source of N₂O, the CFF Calculator would underestimate the effects
407 of this.

408 It is unclear as to why results from the CPLANv0 calculator were consistently lower than the
409 general grouping; the information supplied by the developers appears to suggest that the methodology
410 follows IPCC (2006) Guidelines. Impeding further investigation is the fact that results from this tool are
411 not disaggregated by source category.

412 *3.3.2. Embedded Emissions*

413 Estimates of embedded emissions varied considerably, and were the largest emissions category after
414 livestock (Fig. 3). The CPLANv0 calculator was exempted from this assessment, as it did not appear to
415 consider embedded emissions from any sources, though a lack of disaggregation of results made it difficult
416 to ascertain this in the case of fertiliser.

417 Differences of scope between tools can explain a large amount of this variation (Table 2). Where possible,
418 the scope was determined from information supplied by the tool developers; however, it was frequently
419 necessary to infer this information from data input requirements. Consistent scoping of farm-level tools,
420 particularly in the context of embedded emissions, represents a challenge for developers. These results
421 make it clear that until such a consensus is reached, is important for users to be aware of the impacts this
422 can have on total estimates.

423 *3.3.3. Fuels*

424 Whilst showing some variation, emissions estimates were relatively consistent between tools, with the
425 exception of CPLANv0, which markedly underestimated by comparison (Fig. 3). Except to note that low
426 estimates appear to be typical of the CPLANv0 tool, it is difficult to ascertain why this may be, as the
427 developers did not state which methodology was applied.

428 For the Cool Farm Tool and AgRE Calc however, the methodology used to compute emissions
429 from this source is known; Hillier et al. (2011) state that the Cool Farm Tool uses and EcoInvent database
430 (Ecoinvent Centre, 2007), whilst AgRE Calc uses the publicly available DEFRA/DECC (2011) Emission
431 Factors for Company Reporting (SRUC, 2014). These tools provided similar average estimates, whilst the
432 CALM Tool and CFF Calculator provided estimates which, though of uncertain provenance, were
433 consistent with the group trend.

434 It is worth noting that the fraction of farm-level emissions stemming from fossil fuel use is not
435 high, varying from 2.5 to 11.0% of the net total emissions for the sample farms ($M = 6.2\%$, $N = 35$).
436 Consequently, where variability in estimates for this category is minor, it is unlikely to markedly affect the
437 overall total.

438 *3.3.4. CO₂ Sequestration*

439 Before examining tool results for CO₂ sequestration, it should be acknowledged that the benefits of carbon
440 sequestration by woodland as an approach to offset farm-level GHG emissions are the subject of complex
441 debate (Cannell, 1999) and ongoing research (Feliciano et al., 2013). Whilst the full extent of this debate
442 falls outside the scope of the present study, it is considered here as this component of the GHG footprint is
443 universally included by the present sample of tools.

444 Estimates made by the tools for CO₂ sequestration also showed considerable disparity (Fig. 3).
445 Some explanation for this disparity may well lie in the number of methodologies available to calculate
446 sequestration by woodland, with methodologies provided by the US Forest Service, UK Forestry
447 Commission as well as the IPCC (2006) Guidelines. The latter has been adopted by both AgRE Calc and
448 the CALM tool.

449 As a global methodology, the IPCC (2006) Guidelines supply limited data for temperate
450 woodlands. Estimates of sequestration from AgRE Calc ($m = 405.7 \text{ t CO}_2 \text{ y}^{-1}$, $n = 7$) and the CALM tool
451 ($m = 474.8 \text{ t CO}_2 \text{ y}^{-1}$, $n = 7$) exceed others by a considerable margin; it may be that the lack of data has led

452 to generalisations which overestimate CO₂ sequestration as compared to other methodologies. Comparison
453 with an estimate manually produced for the seven farms using the (UK-specific) Forestry Commission's
454 Carbon Lookup Tables (West and Matthews, 2012) ($m = 269.2 \text{ t CO}_2 \text{ y}^{-1}$, $n = 7$), falls closer to the lower
455 estimates from other tools, supporting this speculation.

456 The CFF Calculator produced the median estimate for this category ($Mdn = 189.6 \text{ t CO}_2 \text{ y}^{-1}$);
457 whilst this value is somewhat lower than the Forestry Commission-derived estimate, the references given
458 for the tool (CFF, 2012) suggest that this source was used by the developers. This being the case, the
459 disparity between the manually calculated estimates ($m = 269.2 \text{ t CO}_2 \text{ y}^{-1}$) and the results of the CFF
460 Calculator ($m = 189.6 \text{ t CO}_2\text{-eq y}^{-1}$) demonstrates the consequence of differing interpretations of this
461 methodology.

462 The Cool Farm Tool's sequestration assessment required input of species composition and trunk
463 diameter change over a one-year period. The available data did not allow for this level of detail, and
464 assumptions made in this respect can significantly influence results. As such, comparison to other tools
465 would have limited validity, and the decision was made to avoid producing a potentially misleading
466 estimate. Users of the Cool Farm Tool without access to specialist forestry data would face a similar
467 decision.

468 The sequestration estimate of the CPLANv0 tool, whilst low, was higher in relative terms
469 compared to its estimates for other emissions sources. Thus, the balance of emissions vs. sequestration
470 reported by this tool is likely to differ in comparison to other tools. Where sequestration is used to offset
471 emissions from other parts of a farming system, this difference will substantially affect how that system is
472 seen to perform.

473 Several tools went into greater depth in this area than could be explored using the sample data.
474 The Cool Farm Tool has the ability to assess emissions/sequestration from land use change (LUC) for up
475 to a maximum of 20 years, as well as changes in tillage practice and use of cover crops. The CFF
476 Calculator considers sequestration not only from woodland, but also from single trees, hedges, field
477 margins, orchards, vineyards, soil and wetlands. The CPLANv0 tool has the facility to assess
478 emissions/sequestration from LUC since the year 1957 in addition to forestry. Finally, whilst the CALM
479 calculator limits its approach to woodland, it includes the facility to assess managed woodland in detail
480 according to species, age and management strategy. Whilst it was not possible to empirically assess the

481 effect of these differences in scope using the sample data, it is certain that the output would be affected.

482 This difference may be substantial, depending upon the extent of these features in a given system.

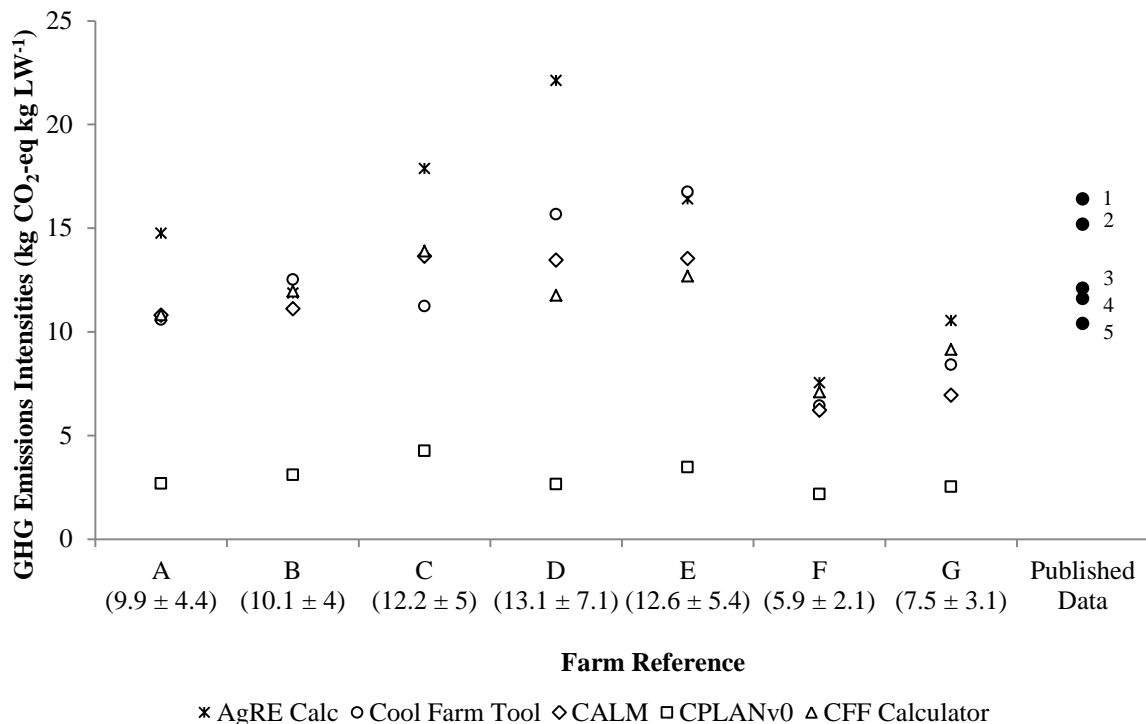
483

484 **3.4. Emissions Intensities and Allocation**

485 GHG emissions intensities for beef production, in kg CO₂-eq kg beef LW⁻¹ were calculated for each farm
 486 ($n = 7$) and each tool ($n = 5$) as described in Section 2.3, creating a total of 35 estimates.

487 The mean emissions intensities calculated by the tools (Fig. 4) show some similarity to those
 488 published in LCA literature. It is important to note that the LCA estimates shown are based on studies of a
 489 range of systems and scales and so direct comparisons should be made with extreme caution; however,
 490 broadly speaking this similarity does appear to indicate some consistency in approach between LCA
 491 practitioners and developers of these farm-level models.

492



493

494 **Figure 4.** Emissions intensities calculated for each farm and tool ($N = 35$). The calculated mean estimate from the five tools
 495 ± 1 S.D. are shown in parentheses. Emissions intensities from a range of published LCA literature are shown in the final
 496 column, for which the sources are 1) Nguyen et al. (2012) (a calculated average from four systems); 2) Vergé et al. (2008);
 497 3) Beauchemin et al. (2011); 4) Vergé et al. (2008); and 5) Casey and Holden (2006). For values 1) and 3), a conversion

498 factor of 1/0.55 (Opio et al., 2013) was applied to convert the published values from kg Carcass Weight (CW) to kg Live
499 Weight (LW).

500

501 Farm D showed the greatest mean emissions intensity ($m = 13.1 \pm 7.1$ kg CO₂-eq kg LW⁻¹), though this
502 was not markedly larger than the highest published values. It is likely that the magnitude of this estimate is
503 a result of the intensive nature of this farming system. The high variability in estimates for this farm is
504 likely to stem from the large pig unit present in the system; when assessing the whole-farm estimates
505 (Section 3.1) it was noted that the tools varied considerably in the estimates produced for this enterprise.
506 More generally, a higher range for the emissions intensity appears to correspond to systems showing a
507 more complex array of enterprise types.

508 The relatively low mean estimate for Farm F ($m = 5.9 \pm 2.1$ kg CO₂-eq kg beef LW⁻¹) is likely to
509 stem from the fact that the main output for this farm is a dairy enterprise, the offspring from which are
510 retained and finished for beef. This is not directly comparable with the published values (Fig. 4), which
511 relate to dedicated beef systems. Here, the majority of emissions from breeding animals are associated with
512 the dairy enterprise, and the system avoids the overheads present in a typical suckler system. Farm G ($m =$
513 7.5 ± 3.1 kg CO₂-eq kg beef LW⁻¹) is a typical suckler system; emissions from this enterprise are low due
514 to an avoidance of inputs such as fertiliser and pesticides. As a consequence of this, the tools which
515 produced the highest results for this farm were those which, on average, attributed the greatest values to
516 enteric emissions estimates (AgRE Calc, CFF and the Cool Farm Tool). The estimates of these tools were
517 comparable to the lower bounds of the published data (Fig. 4).

518 The CPLANv0 tool consistently forms the lower bound of estimates. The average emissions
519 intensity, as calculated by this tool across the enterprises ($m = 3.0$ kg CO₂-eq kg beef LW⁻¹, $n = 7$) falls far
520 below any of the published values shown in Fig. 4, indicating a significant methodological disparity
521 between the CPLANv0 tool and these studies. AgRE Calc typically forms the upper bound of estimates;
522 this is likely due to a number of factors identified thus far. Use of IPCC (2006) Tier II level methods for
523 calculation of direct livestock emissions is likely to have increased this part of the estimate above those
524 tools which follow Tier I methodology. Additionally, AgRE Calc was shown to have the broadest scope
525 for the embedded emissions sources present in the sample datasets; thus, inclusion of these likely further
526 increased the estimate beyond other tools. The Cool Farm Tool, the CALM Tool and the CFF Calculator

527 are generally relatively closely grouped, though the order of this grouping varies somewhat between farms
528 (Fig. 4). In neglecting major sources of N₂O from the estimate, the CFF Calculator is relatively low for
529 farms where N fertiliser use is high (e.g. Farms D and E), though high estimation of the magnitude of
530 embedded emissions may counter this to some extent. Where enteric emissions make up a higher
531 proportion of the total, the CALM Tool appears to fall below the general grouping due to the lower
532 emphasis it places on this emissions source (e.g. Farm G).

533

534 **4. Conclusions**

535 The broad range of sample data allows for some consideration of tools' fitness-for-purpose in the context
536 of footprinting livestock systems. In the absence of an accepted, harmonised methodology for farm level
537 tools, this conclusion avoids making explicit recommendations on tool fitness-for-purpose, but seeks to
538 explore possible criteria for this in the light of tools' performance on real-world livestock enterprises.

539

540 ***4.1. Tool transparency***

541 In any such application, transparency of tool methodology is an important consideration,
542 accounting for inevitable variation and allowing informed comparisons to be made. A lack of transparency
543 in methodology was found to be a major issue for several tools, limiting the insights which could be
544 gained. Hillier et al. (2011) took steps to address this through publication in the case of the Cool Farm
545 Tool, though in some cases it remains unclear what method is being followed. Developers of the CALM
546 Tool and CFF Calculator provided some information on methodology, though lack of detail made it
547 difficult to assess exactly how results were calculated. Developers of the CPLANv0 tool stated that IPCC
548 (2006) Guidelines were used but gave no further information as to additional sources of methodology.
549 Seeking to address this issue for AgRE Calc, methodological sources for this tool are presented for the first
550 time in this paper (Section 2.1.1). Methodological transparency and availability of information is likely to
551 be a key concern where these tools are sought to inform policy (Hall et al., 2010), and hence is a potential
552 limiting factor in the uptake of tools by policy makers. It may also limit the extent to which users can
553 employ the tools make informed decisions on mitigation of emissions from farming systems.

554
555
556

557 **4.2. Tool methodology**

558 Studies have demonstrated the importance of nitrous oxide emissions from cultivation of palm oil
559 and sugar cane (Keller et al., 2014), wheat (Whittaker et al., 2013), and several additional cereal
560 cultivation scenarios (Lewis et al., 2013). This study shows the same is true in the case of livestock
561 systems, not least because such systems are likely to feed the livestock enterprise. Estimates of land and
562 crop emissions by the CALM tool, the Cool Farm Tool and AgRE Calc showed reasonable parity in the
563 results, whilst those of CPLANv0 and the CFF tool were considerably lower. In the case of the CFF tool it
564 is known that the developers omitted several sources of N₂O (Whittaker et al., 2013), which accounts for
565 the low estimate; for the CPLANv0 tool, the reason for this is not known since IPCC methodology is stated
566 to have been followed. Users should be aware that omissions or underestimation of this emissions source
567 may significantly affect the size of the overall footprint. Additionally, where these tools are employed as
568 decision aids for measures aimed to reduce N₂O emissions, the efficacy of such approaches may be
569 underestimated.

570 Estimates of emissions from livestock and manure showed reasonable parity between tools, with
571 the exception of CPLANv0, which again markedly underestimated. Results from the study data show this
572 to be the largest emissions source with the potential to significantly impact results if inconsistently
573 handled. Calculated emissions from manure showed most variability within the category; not all of this
574 was explicable with the available information, and may be due to differing interpretations of the IPCC
575 (2006) guidelines and manure storage categories. The Cool Farm Tool (Hillier et al., 2011) showed the
576 most notable difference in this area. The implications of this are important for users to recognise, given
577 that manure has been shown to offer considerable mitigation potential both in terms of diet (Mathot et al.,
578 2012) and storage management (Masse et al., 2008). Where it is unclear precisely how these emissions are
579 calculated, users should be wary of employing tools to estimate the efficacy of related mitigation measures.

580 Calculation of embedded emissions (emissions from production of agrochemicals and feeds)
581 varied considerably and in some cases represented the second largest emissions category behind livestock.

582 The differing scopes of assessment for this category (section 3.3.2) appear to be largely responsible for
583 these differences. Harmonisation of tool methodologies in this respect should be a key aim for those with
584 development oversight, and users should be aware of the impact such disparities can have on the footprint.
585 Crucially, in the context of decision-making for cleaner production, omission by some tools of certain
586 embedded emission sources may lead to false economies through uneven consideration of trade-offs.

587 Emissions from fuel and electricity, as estimated, were relatively consistent between tools, again
588 with the exception of CPLANv0. As the smallest emission category, it appears the slight differences
589 present here are not of great concern to tool users, though as with embedded emissions, the consideration
590 of this category may be important to prevent false economies of mitigation.

591 Considerable variation, reflective of disparity in the methodologies employed, was present in the
592 estimation of CO₂ sequestration. In particular, the IPCC (2006) methodology, as applied by two tools,
593 appears to be insufficient to account for much variation in British woodlands, and overestimates CO₂
594 sequestration at least with respect to other, country-specific methodologies. The issue of variable
595 methodologies is exacerbated given that the efficacy of GHG offset through biomass sequestration is not
596 clear-cut (Cannell, 1999), and the complex nature of this component is at odds with its simplistic “positive
597 vs. negative” representation in the tools. Further complication may be added where these woodlands are
598 actively managed (Proietti et al., 2016). In the context of biomass sequestration as a means to promote
599 cleaner production, such simplification is a very important consideration for tool users and policy makers
600 to be aware of. For the tools, a level of consensus on both the scope of assessment for CO₂ sequestration,
601 and on the methodology employed, would be advantageous.

602 Finally, it is worth noting that no tools provide estimates of uncertainty alongside the footprints
603 produced. From a scientific standpoint, simplistic GHG modelling such as this carries significant
604 uncertainty; however, this is complex to calculate and interpret, and may not be relevant to the aims of
605 many users. However, it is important to be aware, particularly if tools are employed to guide policy
606 decisions, that even where methodology is transparent, estimates nonetheless carry a degree of uncertainty.

607

608 ***4.3. Allocation within tools***

609 For benchmarking applications, or to facilitate comparisons between farms, it becomes necessary convert
610 the farm-level estimate into a standardised functional unit (e.g. kg CO₂-eq / kg product). Allocation of
611 emissions is a key issue in this respect, with complexity of typical livestock systems amply demonstrated
612 by the sample data. Cropping enterprises footprinted by previous tool reviews considered only single-
613 output enterprises and hence did not encounter this issue.

614 In more complex systems, where a farming system produces more than one product type, tool
615 users must allocate emissions between enterprises in order to separate the product footprints. This may be
616 beyond the skills of an average user, and decisions made at allocation stage have been shown to
617 significantly affect results (Nguyen et al., 2012); thus, it is advantageous that it be performed according to
618 standardised, transparent methodology by the tool itself. Since cleaner production aims are likely to focus
619 on product emissions intensity, rather than farm-level footprint, the ability to consistently separate
620 footprints for mixed enterprises is important. Those with oversight on tool development should be aware of
621 this requirement, and users should be aware of this issue where tools are used to inform decisions or
622 policy. Whilst the requirement to allocate is recognised by some tool developers, the only tool in the
623 current sample with the capability to perform this operation was AgRE Calc.

624

625 ***4.4. Final summary***

626 It has been well recognised that the broad scope of farm-level tools such as these represents a
627 considerable strength (Schils et al., 2007), and their performance in the context of this assessment
628 exemplifies this; however, to obtain this advantage requires the compilation of a broad range of
629 methodologies. This study highlights the hazards associated with such an approach, particularly where tool
630 transparency is lacking. Previous reviews have highlighted, in the context of crop production, the
631 requirement to harmonise tool methodology for consistency in results. This study backs that conclusion in
632 the context of livestock enterprises, and the conclusions presented herein provide a decision aid for users to
633 select an appropriate tool for their required purpose. This study additionally finds that even where
634 estimates appear consistent, variation in the component parts of an estimate may exist independently of
635 variation in the whole. Tools may therefore react differently to changes in the modelled system, and as a
636 result should be used with caution to inform mitigation strategies.

637 It is important that users of farm-level tools acknowledge these issues and treat results with
638 appropriate caution. Where a tool is sought to assist in the derivation or assessment of cleaner production
639 aims, or for the purpose of influencing or informing policy decisions (e.g. Hall et al., 2010), it is vitally
640 important that variation be accounted for, and that areas of opacity in methodology be recognised. Whether
641 prospective tool users are primary producers or policy makers, this study provides a reference point for
642 tool selection and use. Similarly, it provides a synthesis of the state of the art which will be of use to
643 developers in furthering these tools in their ability to provide consistent environmental assessment and
644 decision support for cleaner agricultural production.

645

646

647 **Acknowledgements**

648 The authors would like to thank J Sainsbury PLC for funding this work as part of a PhD studentship.
649 Additional contributions to this research project were funded by the Scottish Government and Innovate
650 UK. The authors would also like to thank the research community within SRUC, and in particular Dr Cath
651 Milne, for providing feedback during the development of this project.

652

653 **Funding**

654 Funding for this project was provided primarily by Innovate UK through J Sainsbury PLC
655 [TS/K003895/1].

656

657 **References**

- 658 Beauchemin, K.A., Janzen, H.H., Little, S.M., McAllister, T. A., McGinn, S.M., 2011. Mitigation of
659 greenhouse gas emissions from beef production in western Canada – Evaluation using farm-based
660 life cycle assessment. *Anim. Feed Sci. Technol.* 166-167, 663–677.
661 doi:10.1016/j.anifeedsci.2011.04.047
- 662 Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Modeling global annual N₂O and NO emissions
663 from fertilized fields. *Global Biogeochem. Cycles* 16, 28–1–28–9. doi:10.1029/2001GB001812

- 664 BSI, 2011. PAS 2050:2011 Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions
665 of Goods and Services. British Standards Institute, London, UK. URL
666 shop.bsigroup.com/forms/PASs/PAS-2050/ (accessed 19.6.17)
- 667 Cannell, M.G.R., 1999. Growing trees to sequester carbon in the UK: answers to some common questions.
668 *Forestry* 72, 237–247. doi:10.1093/forestry/72.3.237
- 669 Casey, J.W., Holden, N.M., 2006. Quantification of GHG emissions from suckler beef production in
670 Ireland. *Agric. Syst.* 90, 79–98. doi:10.1016/j.agsy.2005.11.008
- 671 CFF, 2012. Calculator resources | Farm Carbon Calculator. URL
672 www.cffcarnoncalculator.org.uk/resources/calculator-resources (accessed 7.22.15).
- 673 CLA, 2009. CALM Carbon Calculator: Country Land and Business Association. URL
674 www.calm.cla.org.uk/index.php?section=further_reading (accessed 10.14.14).
- 675 Colomb, V., Bernoux, M., Bockel, L., Chotte, J.-L., Martin, S., Martin-Phipps, C., Mousset, J., Tinlot, M.,
676 Touchemoulin, O., 2012. Review of GHG calculators in agriculture and forestry sectors - A
677 Guideline for Appropriate Choice and Use of Landscape Based Tools.
- 678 Committee on Climate Change, 2010. The Fourth Carbon Budget - Reducing emissions through the 2020s.
679 London, UK. URL [www.theccc.org.uk/publication/the-fourth-carbon-budget-reducing-emissions-](http://www.theccc.org.uk/publication/the-fourth-carbon-budget-reducing-emissions-through-the-2020s-2/)
680 [through-the-2020s-2/](http://www.theccc.org.uk/publication/the-fourth-carbon-budget-reducing-emissions-through-the-2020s-2/) (accessed 19.6.17)
- 681 Committee on Climate Change, 2008. Building a low-carbon economy – the UK’s contribution to tackling
682 climate change, Global Environmental Change. The First Report of the Committee on Climate
683 Change. London, UK. URL [www.theccc.org.uk/publication/building-a-low-carbon-economy-the-](http://www.theccc.org.uk/publication/building-a-low-carbon-economy-the-uks-contribution-to-tackling-climate-change-2/)
684 [uks-contribution-to-tackling-climate-change-2/](http://www.theccc.org.uk/publication/building-a-low-carbon-economy-the-uks-contribution-to-tackling-climate-change-2/) (accessed 19/6/17) doi:10.3763/ehaz.2009.0020
- 685 De Klein, C., Novoa, R.S.A., Ogle, S., Smith, K.A., Rochette, P., Worth, T.C., 2006. Volume 4, Chapter
686 11 - N₂O Emissions from Managed Soils, and CO₂ Emissions from Lime and Urea Application, in:
687 IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan. URL [www.ipcc-](http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html)
688 [nggip.iges.or.jp/public/2006gl/vol4.html](http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html) (accessed 19/6/17).
- 689 DEFRA/DECC, 2013. NAEI, UK National Atmospheric Emissions Inventory. London, UK. URL
690 naei.defra.gov.uk/ (accessed 4.05.17).
- 691 DEFRA/DECC, 2011. GHG Conversion Factors for Company Reporting. London, UK. URL
692 www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2011/ (accessed
693 4.05.17).
- 694 Domingo, J., De Miguel, E., Hurtado, B., Metayer, N., Bochu, J.-L., Pointereau, P., Pellerin, S., Bamiere,
695 L., Pardon, L., 2014. Measures at Farm Level to Reduce Greenhouse Gas Emissions from EU
696 Agriculture. EU Parliament’s Committee on Agriculture and Rural Development.
- 697 Dong, H., Mangino, J., McAllister, T.A., 2006. Volume 4, Chapter 10 - Emissions from Livestock and
698 Manure Management, in: IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan.
699 URL www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (accessed 19.6.17).
- 700 Ecoinvent Centre, 2007. Ecoinvent data v2.0. Ecoinvent reports No. 1e25. Swiss Centre for Life Cycle
701 Inventories, Dübendorf. URL www.ecoinvent.org (accessed 19.6.17)
- 702 Eshel, G., Shepon, A., Makov, T., Milo, R., 2014. Land, irrigation water, greenhouse gas, and reactive
703 nitrogen burdens of meat, eggs, and dairy production in the United States. *Proc. Natl. Acad. Sci.* 111,
704 11996–12001. doi:10.1073/pnas.1402183111

- 705 INRA, 2012. Feedipedia Animal Feed Resources Information System | An on-line encyclopedia of animal
706 feeds. INRA, CIRAD, AFZ and FAO. URL www.feedipedia.org/ (accessed 19.6.17).
- 707 Feliciano, D., Hunter, C., Slee, B., Smith, P., 2013. Selecting land-based mitigation practices to reduce
708 GHG emissions from the rural land use sector: A case study of North East Scotland. *J. Environ.*
709 *Manage.* 120, 93–104. doi:10.1016/j.jenvman.2013.02.010
- 710 Hall, P., Holmes-Ling, P., Stewart, K., Sheane, R., 2010. A Scottish Farm-Based Greenhouse Gas
711 Accounting Tool for Scotland. Laurence Gould Partnership Ltd. and Best Foot Forward Ltd., Scottish
712 Government.
- 713 Hillier, J., Walter, C., Malin, D., Garcia-Suarez, T., Mila-i-Canals, L., Smith, P., 2011. A farm-focused
714 calculator for emissions from crop and livestock production. *Environ. Model. Softw.* 26, 1070–1078.
715 doi:10.1016/j.envsoft.2011.03.014
- 716 IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan. URL
717 <http://www.ipcc-nggip.iges.or.jp/public/2006gl/> (accessed 19.6.17)
- 718 Keller, E., Chin, M., Chorkulak, V., Clift, R., Faber, Y., 2014. Footprinting farms: a comparison of three
719 GHG calculators. *Greenh. Gas Meas. Manag.* 37–41. doi:10.1080/20430779.2014.984609
- 720 Kool, A., Marinussen, M., Blonk, H., 2012. LCI data for the calculation tool Feedprint for greenhouse gas
721 emissions of feed production and utilization: GHG Emissions of N, P and K fertilizer production.
722 Blonk Consultants.
- 723 Lewis, K.A., Green, A., Warner, D.J., Tzilivakis, J., 2013. Carbon accounting tools : are they fit for
724 purpose in the context of arable cropping ? Carbon accounting tools : are they fit for purpose in the
725 context of arable cropping ? *Int. J. Agric. Sustain.* 11, 159–175.
- 726 Masse, L., Claveau, S., Benchaar, C., Thomas, O., 2008. Methane emissions from manure storages. *Trans.*
727 *Am. Soc. Agric. Biol. Eng.* 51, 1775–1781.
- 728 Mathot, M., Decruyenaere, V., Stilmant, D., Lambert, R., 2012. Effect of cattle diet and manure storage
729 conditions on carbon dioxide, methane and nitrous oxide emissions from tie-stall barns and stored
730 solid manure. *Agric. Ecosyst. Environ.* 148, 134–144. doi:10.1016/j.agee.2011.11.012
- 731 Moran, D., Macleod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, R., Topp, C.F.E., Moxey, A.,
732 2011. Marginal Abatement Cost Curves for UK Agricultural Greenhouse Gas Emissions. *J. Agric.*
733 *Econ.* 62, 93–118. doi:10.1111/j.1477-9552.2010.00268.
- 734 Nguyen, T.T.H., van der Werf, H.M.G., Eugène, M., Veysset, P., Devun, J., Chesneau, G., Doreau, M.,
735 2012. Effects of type of ration and allocation methods on the environmental impacts of beef-
736 production systems. *Livest. Sci.* 145, 239–251. doi:10.1016/j.livsci.2012.02.010
- 737 Proietti, P., Sdringola, P., Brunori, A., Ilarioni, L., Nasini, L., Regni, L., Pelleri, F., Desideri, U., Proietti,
738 S., 2016. Assessment of carbon balance in intensive and extensive tree cultivation systems for oak,
739 olive, poplar and walnut plantation. *J. Clean. Prod.* 112, 2613–2624.
740 doi:10.1016/j.jclepro.2015.10.009
- 741 Schils, R.L.M., Olesen, J.E., del Prado, a., Soussana, J.F., 2007. A review of farm level modelling
742 approaches for mitigating greenhouse gas emissions from ruminant livestock systems. *Livest. Sci.*
743 112, 240–251. doi:10.1016/j.livsci.2007.09.005
- 744 SEE360, 2007. Cplan | The Carbon Emissions Calculator for Farms and Agriculture Industries. URL
745 www2.cplan.org.uk/index.php?_load=page&_pageid=1 (accessed 10.9.14).

- 746 SRUC, 2014. AgRE Calc. URL
747 [www.sruc.ac.uk/info/120355/carbon_and_climate/1333/agricultural_resource_efficiency_calculator_](http://www.sruc.ac.uk/info/120355/carbon_and_climate/1333/agricultural_resource_efficiency_calculator_agre_calc)
748 [agre_calc](http://www.sruc.ac.uk/info/120355/carbon_and_climate/1333/agricultural_resource_efficiency_calculator_agre_calc)
- 749 Vergé, X.P.C., Dyer, J. a., Desjardins, R.L., Worth, D., 2008. Greenhouse gas emissions from the
750 Canadian beef industry. *Agric. Syst.* 98, 126–134. doi:10.1016/j.agry.2008.05.003
- 751 West, V., Matthews, R., 2012. Carbon Look up table. Forestry Commission, Bristol, UK. URL
752 www.forestry.gov.uk/forestry/inf-d-8jue9t (accessed 19.6.17)
- 753 Whittaker, C., McManus, M.C., Smith, P., 2013. A comparison of carbon accounting tools for arable crops
754 in the United Kingdom. *Environ. Model. Softw.* 46, 228–239. doi:10.1016/j.envsoft.2013.03.015
- 755 Xu, X., Lan, Y., 2016. A comparative study on carbon footprints between plant- and animal-based foods in
756 China. *J. Clean. Prod.* 112, 2581–2592. doi:10.1016/j.jclepro.2015.10.059
- 757 Yan, M., Cheng, K., Luo, T., Yan, Y., Pan, G., Rees, R.M., 2015. Carbon footprint of grain crop
758 production in China – based on farm survey data. *J. Clean. Prod.* 104, 130–138.
759 doi:10.1016/j.jclepro.2015.05.058