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Life cycle greenhouse gas emissions from integrated organic farming: a systems approach considering rotation cycles

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Abstract

Integrated organic farming could help reduce greenhouse gas (GHG) emissions and other environmental impacts from agriculture but studies of such practices are scarce, particularly those considering farms as whole systems and taking into account rotation cycles. To address this knowledge gap, this study considers life cycle GHG emissions and the related global warming potential (GWP) of a large integrated organic farm in the UK. The farm produces arable crops (wheat, oats, barley, beans and rye), silage and straw, livestock (dairy and beef cows, sheep/lambs and pigs) and related meat products as well as milk and wool. To ensure that the variations in the emissions with crop rotation are taken into account, the study covers a seven-year rotation cycle. The results suggest that the annual GWP of the whole farming system varies from 1816 to 2372 t CO₂e over the rotation period, averaging 2118 t CO₂e/yr or 2.65 t CO₂e/ha. Dairy and beef cattle are the main contributors, causing 45% and 39% of GWP, respectively; this is mainly due to emissions of methane from enteric fermentation and nitrous oxide from manure. Crop cultivation adds a further 10% to the impact, while the contribution of sheep and pig husbandry is relatively small (6% and <1%, respectively). Per kilogram of meat, lamb and beef have the highest impact, estimated at 12-17.8 and 15.8-18.9 kg CO₂e, respectively. By comparison, GWP from pig meat ranges from 5.6 to 8.5 kg CO₂e/kg, largely caused by feed concentrate. The impact from milk production is estimated at 1.02-1.21 kg CO₂e/l, mostly related to methane emissions from enteric fermentation. The GWP from wool ranges from 20.8-30.9 kg CO₂e/kg. Among the crops, beans have the highest average impact (692 g CO₂e/kg) and rye the lowest (157 g CO₂e/kg). The hotspots for the crops are emissions of nitrous oxide from manure application to land and use of diesel in farm machinery. A sensitivity analysis shows that the assumptions for allocating N₂O emissions over the rotation cycle have a significant effect on the results. Options for reducing GHG emissions include intercropping, optimisation of feed composition and anaerobic digestion of waste.

Keywords: *global warming potential; greenhouse gas emissions; integrated organic farming; life cycle assessment; organic produce*

1. Introduction

With 6.1 billion tonnes of CO₂e emitted in 2011, agriculture contributes 18% to global greenhouse gas (GHG) emissions (FAOSTAT, 2015; Olivier *et al.*, 2012). In the UK, it is the second largest source of GHG emissions, after the energy sector, contributing around 9% to total annual emissions (Webb *et al.*, 2014). Although global emissions from agriculture have increased by 17% between 1990 and 2011 (FAOSTAT, 2015), in the UK they have shown an opposite trend, decreasing by 20% over the period. This is due mostly to the decreasing livestock numbers and use of fertilisers (Webb *et al.*, 2014). GHG emissions from agriculture arise mainly from three gases: nitrous oxide (N₂O), methane (CH₄) and carbon dioxide (CO₂). N₂O emissions are mainly caused by application of fertilisers and manure (both applied and excreted on pasture) to soils, which contribute 12% and 26% to the global GHG emissions from agriculture, respectively (see Figure 1). The main sources of CH₄ emissions are enteric fermentation of dairy, beef and sheep herds (40%) and manure (26%). CO₂ emissions are also attributable to manure management and to combustion of fuel used for farming activities.

Key recommendations made by expert groups to reduce GHG emissions from agriculture include crop rotations, nutrient recovery and recycling through manure management, improving livestock productivity, pasture and fodder improvements as well as maintenance of soil fertility (Niggli *et al.*, 2009; Gerber *et al.*, 2013). These practices are typically used in organic agricultural systems. However, yields of organic

crops are generally lower than those of conventional produce due to challenges in maintaining nutrient availability in organic systems (Ponti, *et al.*, 2012).

Figure 1 Average contribution of different agricultural activities to global greenhouse gas emissions from agriculture in the period 1990-2011 (FAOSTAT, 2015)

Organic agriculture is defined by the International Federation of Organic Agriculture Movements (IFOAM, 2008) as a “production system that sustains the health of soils, ecosystems and people”. This definition also emphasises its reliance on ecological processes, biodiversity and natural cycles. Four key principles guide organic agricultural practices: health, ecology, fairness and care. Integration of arable crops and animal husbandry into organic farming systems, also referred to as “integrated organic farming” (Panda, 2013), can provide a number of benefits: it fosters internal recycling of nutrients; external inputs are reduced; and it can build self-sufficiency of the farm by reducing purchases of animal feed and concentrates (Peyrauda *et al.*, 2014). It has also been suggested that integrated organic farming systems could help reduce GHG emissions from agriculture (Niggli *et al.*, 2008).

However, studies considering GHG emissions from integrated organic systems are scarce, with most focusing on a single organic produce rather than a farm as an integrated system (for a review see e.g. Roy *et al.*, 2009 and Meier *et al.*, 2015). An exception is a life cycle assessment (LCA) study by Cooper *et al.* (2011), which considered an eight-year crop rotation cycle to estimate GHG emissions from an integrated organic system producing crops and livestock. However, the emissions were expressed per hectare rather than at the systems or product level. Marton *et al.* (2016) also assessed GHG emissions of an organic crop-livestock system, but without considering crop rotation and expressing the emissions only at the farm level. Other LCA studies compared GHG emissions of conventional and organic farming in Europe (for a review, see Tuomisto *et al.*, 2012a), showing that organic farming practices generally have lower impacts on the environment per unit of area compared to conventional farming, but not necessarily per unit of product, because of generally lower yields. Specifically, organic beef, olives and some other crops had lower GHG emissions while those from organic milk, cereals and pork were higher compared to conventional products (Tuomisto *et al.*, 2012a).

As observed by Nemecek *et al.* (2011), most LCA studies have investigated only the average differences between the farming systems, despite a large variation in environmental impacts within each farm. One reason for the variation in the impacts, particularly from integrated farming systems, is the rotation cycle. This aspect has so far received little attention in the literature so that there is scant information on how different rotation cycles and their duration affect the environmental impacts from farming. Tidaker *et al.* (2014) also note this in their more recent study, recommending that crop sequences rather than single crops be considered when evaluating the impacts of farming systems.

In a given rotation cycle, the previous crop affects the crop that follows because the crop sequence has an effect on the nutrients' turn-over and soil organic and mineral status. For example, crop residues remaining on the field or the introduction of green manure crops or catch crops in the crop rotation can have a major impact on the subsequent crop and on the crop rotation as a whole by affecting the soil properties and fertility and, consequently, the achievable yield (Nemecek *et al.*, 2015; Brankatschk and Finkbeiner, 2015; Peter *et al.*, 2017). These aspects are particularly important in organic agricultural systems which rely to a high degree on recycling of nutrients and using crop residues or green manure crops as a means to fertilise the crops and maintain soil fertility. This constitutes a challenge when using LCA for analysing GHG emissions associated with organic crops, since the crops and their respective yields in an organic crop rotation system are often interlinked through fertility-building (e.g. legumes and beans) and fertility-exploiting crops (e.g. wheat and barley) (Knudsen *et al.*, 2014). Neglecting nutrient shifts from one crop to the subsequent crop leads to free-rider situations for crops that consume nutrients left by the preceding crops (Brankatschk and Finkbeiner, 2015). LCA studies assessing only one crop have a limited ability to include these effects, thus under- or over-estimating the impacts (Tidaker *et al.*, 2014).

In current LCA of agricultural products, most crop-rotation effects are not properly addressed due to methodological challenges (Brankatschk and Finkbeiner, 2015). A number of approaches have been suggested to include crop rotation effects in LCA but so far there is no agreement on how to include the effects of crop rotation in assessing the environmental impacts of a particular crop. Audsley *et al.* (1997) and Van Zeijts *et al.* (1999) proposed allocating the burden associated with the application of organic matter according to the land-use share of each crop in the rotation. Knudsen *et al.* (2014) suggested dividing the environmental burdens and benefits from the catch crops and green manure equally among all crops in the crop rotation cycle over a given area. Use of nitrogen (N) mineralisation rates and N uptake have been suggested for allocating the environmental burdens of manure, catch crops (Knudsen *et al.*, 2012, Tuomisto *et al.*, 2012b) and compost (Martínez-Blanco *et al.*, 2014). In some studies, the burdens of crop residues are allocated to the subsequent crop (Styles *et al.*, 2015) or a by giving a credit for the nutrients to the current crop if a reduced fertiliser dose is recommended for the subsequent crop (Nemecek *et al.*, 2011). Brankatschk and Finkbeiner (2015) recommend using output-based allocation approach to model crop-rotation effects in LCA. The authors suggest using the cereal-unit allocation approach, which is a bio-physical allocation method based on the nutritional value of agricultural products to animals (Brankatschk and Finkbeiner, 2014).

In an attempt to address some of the gaps discussed above and improve knowledge about integrated organic farming and its impact on climate change, this paper considers a fully integrated organic farming system based in the UK. The aim of the study is to estimate life cycle GHG emissions associated with the production of arable crops, livestock and related products. LCA has been used as a tool for this purpose. To ensure that the variations in the emissions with crop rotation over time are taken into account, a seven-year rotation cycle is considered and the results are estimated at both the systems and product levels. The study also highlights various methodological challenges in conducting LCA of such complex systems.

2. Methodology

The study has been carried out following the LCA methodological guidelines in the ISO 14040 and 14044 (ISO, 2006a; ISO, 2006b) and PAS 2050 (BSI, 2011) standards. The following sections detail the goal of the study, data and the assumptions.

2.1 Goal and scope of the study

The goal of the study is to estimate GHG emissions and the related global warming potential (GWP) associated with agricultural production of arable crops, livestock and their products in an integrated organic farming system. The study also aims to identify the main GWP 'hotspots' and opportunities for improvements, following the key principles of integrated organic farming.

The scope of the study is from 'cradle to farm gate'. The functional unit is defined as 'operation of the farm over a seven-year rotation period'. The activities carried out by the farm and considered in the study are described in the next section.

2.2 System definition

The integrated organic farming system considered in this study is a large integrated organic farm in the UK. An overview of the farm is provided below.

2.2.1 *Overview of the farm*

The farm is located in the South West of England and occupies 800 hectares (8 km²) of land. It has been dedicated to organic agriculture for over 30 years, producing arable crops, silage, straw, livestock, meat, milk and wool. The main arable crops are wheat, oats, barley, beans and rye. The livestock comprises a dairy herd of Ayrshire cows, a beef herd of Aberdeen Angus suckler cows and a sheep flock of Lleyen and Lleyen Cross ewes and rams. The farm also raises rare-breed Tamworth/Large black pigs. The products considered in the study over are given in Table 1.

Table 1 Crops and livestock considered in the study

Arable and forage crops	Livestock and related products
Winter milling wheat	Sheep, lamb meat and wool
Spring oats	Pigs and pig meat
Spring beans	Beef cattle and beef meat
Spring barley	Dairy cattle, milk and beef meat
Rye	
Silage	
Straw (from all cereals)	

The majority of the land is cultivated on a seven-year organic rotation cycle. A typical seven-year rotation cycle consists of three years of clover leys (the main source of nitrogen), followed in year 4 by winter wheat, then by spring oats in year 5, spring beans and barley in year 6 and finally by rye in year 7. Composted farmyard manure (FYM) from the dairy and beef cattle is spread on fields during the ley years, adding organic matter and nutrients. Catch and cover crops (turnips, brassicas, and mustard) are sown after harvesting to keep the soil covered, reduce soil and nutrient loss and provide forage.

Field operations vary according to the stage in the rotation cycle and the weather/state of the soil. In the first year of leys, a field would typically have the following operations: shallow cultivation and rolling, grass seed planting, manure spreading and then two to three silage cuts. Subsequent years see further manure applications and silage cuts. For the arable phase, the fields are ploughed, pressed, then harrowed and drilled with a combi-planter, harrow-combed (weeded), harvested with a power combine, then weeded again and cover crops planted. Crops are dried using a diesel grain dryer with electric fan.

Following the principles of organic agriculture, the farm aims to minimise inputs and the cattle, when inside, are fed a home-grown forage and straw-based diet. The dairy cattle diet is also supplemented by cereals – from the farm where possible or else purchased in. Artificial pesticides and fertilisers are prohibited. Lime is applied to fields as necessary to balance the soil acidity and trace elements are added if needed. About 120 hectares of permanent pasture are used for grazing, silage production and to increase biodiversity. Hedgerows and field margins are maintained as barriers to pests and a natural habitat to predators.

2.2.2 *System boundaries*

As shown in Figure 2, the following is included within the system boundaries:

- production of farm inputs and transport to the farm (where relevant);
- manufacture and maintenance of farm machinery and milking parlour equipment;
- production of mineral supplements for the livestock and mineral fertilisers;
- cultivation, harvesting, grain drying and storage of harvested crops;
- plastic film for silage bales;
- animal husbandry and slaughter house activities;
- milking parlour operations; and
- on-farm manure management.

Operation of offices and staff accommodation are excluded from the system boundaries. In accordance with PAS 2050 (BSI, 2011), land use change and soil carbon sequestration are also excluded: the former is not relevant as the land has been used for agriculture for more than 20 years and changes in soil carbon (while they could be significant) are outside the scope of the study.

2.3 Inventory data

Primary data have been obtained from the farm. The secondary (background) data have been sourced from IPCC (2006), CCaLC (2013), DEFRA (2014a) and Ecoinvent (2010). The data sources are summarised in Table 2 with further details provided in the subsequent sections.

2.3.1 Land use

Three main types of land use are defined: grass leys, arable land and grazing pastures. The rotation sequence for the arable crops over the period of the study was discussed in section 2.2.1. All the cattle graze outdoors for six months (May to October) and are housed for the rest of the year. Sheep and pigs, on the other hand, stay outdoors all year round. Pigs are allocated an exclusive area in the farm, whereas sheep and cattle use the same fields (at different times) for grazing.

Figure 2 System boundaries for the farm considered in the study

Table 2 Sources of life cycle inventory data

Data set	Type of data	Source
Farm energy consumption (diesel, electricity)	Primary	Farm
Inputs for cultivation of arable crops (seeds, manure, lime & other nutrients)	Primary	Farm
Crop cultivation operations	Primary	Farm
Livestock (type, number, age groups)	Primary	Farm
Feed for livestock	Primary	Farm
Farm outputs (crop yields, livestock, meat, milk, wool)	Primary	Farm
Emission factors for enteric fermentation, manure management, fertiliser application, leachate	Secondary	IPCC (2006)
GHG emissions from energy (diesel, electricity)	Secondary	DEFRA (2014a)
GHG emission data for farm machinery production, purchased seed and feed concentrates, lime production, water supply	Secondary	Ecoinvent (2010), CCaLC (2013)
Road transport	Secondary	Ecoinvent (2010)

2.3.2 Distribution of resources within the farm

Figure 3 shows the distribution of different resources within the farm. The grassland plots provide grazing animals with fodder, while animals deposit manure (excreta) in return. The FYM deposited during the housing period is collected, composted and applied as organic fertiliser to arable plots as well as

grassland. This is supplemented by dairy cattle slurry and washings from the milking parlour and barns which are collected throughout the year.

The straw obtained as a co-product of cereal cultivation is mainly used as bedding for the dairy and beef cattle as well as for the pigs, which is subsequently composted with FYM. Silage, produced at the farm from chopped grass cuttings, is fed to the dairy and beef cattle during the in-house periods, supplemented by cereal production saved from a previous harvest. Silage is wilted in the field but not otherwise dried before being baled and wrapped in polyethylene film. The cereal crops are largely produced for sale; however, small amounts are kept for seeds for the following year's crop and are also used to prepare mixed feed concentrate for cows-in-milk.

Pigs are fed exclusively with feed concentrate and minerals bought into the farm. The home-grown diet for sheep and the cattle (dairy and beef) is also supplemented with minor quantities of minerals and feed concentrate.

The milk produced by the dairy cattle is largely sold to a processor for bottling and distribution. The average milk yield of dairy cows is 5965 litres per year per cow. Internal consumption of milk is distributed between calves from the dairy herd (up to 12% of the volume produced, depending on the number of calves) and the farm personnel (up to 2.5%). Calves are fed milk only for a minimum of three months before being introduced to forage and grazing. The male young stock from the dairy cattle herd are transferred to the beef cattle herd after their first year of life.

Figure 3 Distribution of resources within the farm

[The dotted lines indicate that grassland is used for arable crops and vice versa in a rotation cycle. Straw is used for bedding for cattle and pigs and cattle feed.]

2.3.3 Crop cultivation

2.3.3.1 Inputs for crop cultivation

Crop cultivation involves various field operations and inputs which vary depending on the crop and stage in the rotation cycle; these are detailed in Table 3. This information has been used to model the annual cultivation activities on each field. However, the sequence of planting the crops within the rotation cycle is not followed strictly in all plots – the study considers the actual rotation cycles for each plot over a seven-year period.

Sheep and cattle graze in the fields in-between the cropping periods of the rotation cycle. The livestock assist in fertilising the soil by direct deposition of manure and are an integral part of grassland management by reducing excess vegetation and increasing tillering. Mustard, forage rape and stubble turnips are planted as cover crops in-between major crops. The crops are rain-fed, so there is no irrigation. The straw from the cereals (wheat, barley, oats and rye) is baled for storage before being used for bedding and cattle feed.

Table 3 Standard field operations and inputs over the rotation cycle

Year	Field operations	Number of passes	Inputs	Application rate
Year 1:	Terradisk	2		
Leys/forage	Power harrow	1		
	Ring-roll	1		
	Harrow comb/grass seeder	1	Grass seed	24.7 kg/ha
	Flat-roll	1		
	Fertiliser application	1 or 2	Manure/slurry	12.4 t/ha
	Silage cut	3		
	Cattle grazing			
Year 2:	Fertiliser application	1 or 2	Manure/slurry	12.4 t/ha
Leys	Sheep grazing			
	Cattle grazing			
Year 3:	Fertiliser application	1 or 2	Manure/slurry	12.4 t/ha
Leys	Silage cut	1		
	Cattle grazing			
Year 4:	5 furrow reversible plough	1		
Winter milling wheat	Press with plough	1		
	Power harrow/drill combi	1	Wheat seeds	144 kg/ha
	Harrow comb	1 if required		
	Combine harvest	1		
	Straw baling	1		
	Terradisk/seed box	1	Mustard, stubble turnip, forage rape seeds	7.4 kg/ha
	Sheep grazing			
Year 5:	Plough	1		
Spring oats	Press with plough	1		
	Power harrow / drill combi	1	Oat seeds	127 kg/ha
	Harrow comb	1 if required		
	Combine harvest	1		
	Straw baling	1		
	Terradisk / seed box	1	Mustard, stubble turnip, forage rape seeds	7.4 kg/ha
Year 6:	Plough	1		
Beans/ Spring barley	Press with plough	1		
	Power harrow/drill combi	1	Bean seeds Barley seeds	254 kg/ha 75 kg/ha
	Harrow comb	3		
	Combine harvest	1		
	Straw baling	1		
	Plough / press	1		
	Combi drill	1	Rye seeds	182 kg/ha
Year 7:	Combine harvest	1		
Rye	Straw baling	1		

In some years in the rotation cycle, a portion of the harvested grains is used as seeds for the next crop as shown in Table 4. Home-grown seeds, however, are not sufficient in most cases and are supplemented with seeds purchased locally, as also indicated in the table.

2.3.3.2 Field operations and crop production

The farm operations that take place over the rotation cycle are summarised in Table S1 in Supplementary Information (SI), together with the total land area covered and the amount of diesel consumed by the farm machinery for different activities. Primary data for diesel consumption have been sourced from the farm and supplemented by data from the literature. However, the values reported in the literature vary significantly, depending on the efficiency of machinery, field topography and soil characteristics. Taking a conservative approach, the highest values for diesel consumption have been assumed in this study.

However, to reflect the actual annual diesel purchases by the farm, correction factors have been applied to the theoretical diesel consumption values given in Table S1. The correction factors vary for each year, as indicated in Table S2 in SI. In all cases, the actual diesel consumption at the farm was lower than the initial estimates calculated using the values reported in the literature (see Table S1 in SI). The amounts of crops produced over the rotation cycle are summarised in Table 5.

2.3.3.3 GHG emissions

Both direct and indirect N₂O are considered, including emissions from the application of organic fertilisers, from cover crops and crop residues as well as from nitrate leaching. The main source of CO₂ emissions is diesel used in farm machinery; the emission factors for the extraction, refining and combustion of diesel have been taken from DEFRA (2014a). CO₂ emissions due to occasional application of lime to correct the soil pH are also considered and have been calculated using the IPCC Tier 2 characterisation factors (IPCC, 2006).

Table 4 Seed and diesel used over the rotation cycle

Farm inputs	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Wheat seeds [t/yr] ^a	7.6	12.35 (49%)	10.4 (100%)	9.8 (44%)	8.7 (100%)	9.5 (21%)	6 (100%)
Oats seeds [t/yr] ^a	10.93	2.52	6	12.28 (90%)	8.85 (26%)	7.5	7.5
Barley seeds [t/yr]	3	2.6	2.95	3.2	5.5	3	5.15
Beans seeds [t/yr] ^a	5.65	4.9	3	3.6 (100%)	7.5	3.5	1
Rye seeds [t/yr] ^a	5	7 (14%)	1.5	1.52	2	2	5.5 (100%)
Forage seeds ^b [t/yr]	1.26	0.85	0.95	0.63	0.52	3	0.6
Diesel consumption [l]	40,103	41,618	40,460	40,865	51,702	53,229	56,435

^a The values in brackets represent the percentage of home-grown seeds with the rest being purchased in.

^b Forage crops are mainly produced from clover (red and white) and ryegrass, and they are used as fodder and for silage.

Table 5 Annual and total production of arable crops and silage over the rotation cycle [tonnes]

Crop	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Total
Winter wheat grains	238	376	464	296	199	216	100	1889
Spring oat grains	362	221	321	320	339	250	300	2113
Spring barley grains	38	175	80	103	103	161	123	783
Spring beans	24	38	9	35	84	17	9	215
Rye grains	127	112	49	51	83	58	79	559
Straw (all crops)	727	725	888	725	782	652	538	5038
Grass silage	1406	1373	1613	1723	1397	1574	977	10,063

2.3.4 Sheep and lamb husbandry unit

A sheep flock of 500 Lleyen and Lleyen Cross ewes and rams is reared at the farm. During the lambing season, the flock size roughly doubles (see Figure S1 in SI). The land occupied for grazing by the sheep and the forage have been allocated on the basis of the number of livestock units, using the allocation factors discussed in section 2.3.10.2. Ewes are fed a supplementary feed concentrate with the ration ranging between 0.01 and 0.04 kg per head per day. The composition of the feed concentrate has been assumed at 15% crude protein, 10.5% crude fibre and 4% oil (The Organic Feed Company, 2011) and is given in Table S3 in SI. Ewes are also fed mineral supplements, but their contribution to the overall GHG emissions is deemed negligible, assuming a concentration of 50 mg of active compounds per litre of supplement (as per manufacturers' specification). Water required for sheep rearing (Swistock, 2009) and the quantity of nitrogen excreted in sheep manure (DEFRA, 2009a) are detailed in Table 6.

The sheep rearing unit has three main outputs: live sheep, lamb meat and wool. Ewes are shorn once a year, assumed to produce 3 kg of wool each (Lampkin, 2008). The total weight of live lambs has been

calculated based on the number of lambs sold plus any change in the stock and the average liveweight per lamb (20 kg); for details, see Table S4 in Supplementary Information. The amount of lamb meat has been estimated using a killing-out percentage (carcass weight as percentage of its liveweight) of 45% (Williams *et al.*, 2006). The annual and total amounts of different products from this unit are summarised in Table 7.

Table 6 Water consumption and nitrogen excretion by sheep

Sheep groups	Age	Weight [kg]	Water consumption [l/day]	Nitrogen excreted [kg N/month]
Ewes + lambs	> 2 years	60	10	0.6
Ewe lambs	1 to 2 years	50	5	0.1
Rams	> 2 years	80	5	1.0
Lambs	< 1 year	20 ^a	4	0.2

^a Average weight of lambs between weaning and finishing.

Table 7 Annual and total products from the sheep, pig and cattle units over the rotation cycle

Product	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Total
Milk [l]	718,809	773,088	812,560	824,383	792,132	748,951	766,624	5,436,547
Milk [kg FPCM] ^a	755,233	812,262	853,734	866,156	832,271	786,902	805,471	5,712,030
Liveweight beef cattle [kg]	72,050	61,170	83,480	73,180	85,800	111,950	103,370	591,000
Beef meat [kg] ^b	39,628	33,644	45,914	40,249	47,190	61,573	56,854	325,050
Liveweight pigs [kg]	2590	2010	3185	2190	2620	3795	1785	18,175
Pig meat [kg] ^b	1865	1447	2293	1577	1886	2732	1285	13086
Liveweight lambs [kg]	13,080	11,320	14,380	8260	9240	7560	8080	71,920
Lamb meat [kg] ^b	5886	5094	6471	3717	4158	3402	3636	32,364
Liveweight sheep (excl. lambs) [kg]	7400	4520	800	7380	8420	4660	12,380	45,560
Wool [kg] ^c	1449	1203	1083	909	1146	1287	1290	8367

^a FPCM: fat and protein corrected milk. Calculated assuming 4.17% of fat and 3.33% of protein in the milk (Hanks and Kossaibati, 2013) as follows (AHDB, 2014): $FPCM = M (0.2534 + 0.1226 \times F + 0.0776 \times P)$, where M is the mass of milk [kg], F the fat and P the protein content [%] in milk. Milk density: 1.027 kg/l.

^b Beef meat: 55% killing-out percentage (KOP); lamb meat: 45% KOP; pig meat: 72% KOP (Williams *et al.*, 2006).

^c Wool: 3 kg/yr obtained from each ewe.

2.3.5 Pig husbandry unit

The size of the pigs herd ranges between 30 and 80 heads over the rotation cycle (see Figure S2 in SI). As indicated in Table 8, pigs are classified into five groups: sows, boars, piglets in lactation, weaners and growers. The table also details the amount of water, feed concentrate and bedding required for pig rearing as well as the excretion of nitrogen. These have been calculated on the basis of the number of pigs, age and weight, also shown in the table.

The composition of the concentrate fed to sows, boars and piglets is given in Table S5 in Supplementary Information. Note that organic agricultural practices require that organic livestock should be fed organic feed concentrate (Edwards, 2002). Exceptions are made in the case of unavailability of organic feed, allowing for feed coming from 'in-conversion' holding or non-organic sources. GHG emissions from the organic feed concentrate have been modelled using data from the Ecoinvent (2010) and CCaLC (2013) databases.

The outputs from the pigs rearing unit are assumed to be grower piglets, with a finishing weight of 35 kg. The total weight of live pigs has been calculated based on the number of grower piglets sold plus any change in the stock and their respective liveweight (as detailed in Table S6 in SI). The total amount of pig

meat produced by the farm has been estimated based on a killing-out percentage of 72% (Williams *et al.*, 2006). The annual and total amounts of pig meat can be found in Table 7.

2.3.6 Beef cattle husbandry unit

A beef herd of 80 to 140 Aberdeen Angus suckler cows and 200 to 300 young stock are reared at the farm. The herd is classified into five groups: cows, bulls, young stock younger than one year, young stock between one and two years old and young stock older than two years. As mentioned before, the herd is housed indoors during the winter months and for the rest of the year it grazes outdoors. Different groups of cattle graze different plots as well as some of the arable land during the fallow period in-between crops. These movements are complex and it was not feasible to allocate each plot to different groups of cattle over the rotation cycle. Instead, the land classified as 'pasture' has been allocated to the herd on the basis of the number of livestock units.

Table 9 details the inputs required for beef cattle rearing and manure they generate (as nitrogen excretion), calculated on the basis of their number, age and weight. The cows-in-milk are fed a concentrate with the composition given in Table S7 in SI.

As for the other livestock, the total weight of beef cattle has been estimated based on the number of animals sold plus any change in the stock and their respective liveweight (Table S8 in SI). The total amount of beef meat produced by the farm has been estimated assuming a killing-out percentage of 55% (Williams *et al.*, 2006). The annual and total amounts of beef are detailed in Table 7.

Table 8 Inputs into the pig units and manure (nitrogen) excretion

Pig groups	Age	Weight [kg]	Water consumption [l/day] (Swistock, 2009)	Feed ration [kg/day] (Martins <i>et al.</i> , 2002)	Bedding ^a [kg straw/month]	Nitrogen excreted [kg N/month] (DEFRA, 2009a; Martins <i>et al.</i> , 2002)
Sows	> 1 year	225	15	1.7	27.2	1.33
Boars	> 1 year	250	15	1.7	27.2	1
Piglets in lactation	Up to 5 weeks	7			6.8	
Weaners	6-10 weeks	18 ^b	2	0.5 -1	13.6	0.5
Growers	11-16 weeks	30 ^b	4.5	1- 2	13.6	0.7

^a Assuming that weaners and growers require half and piglets a quarter of sows' bedding requirements.

^b Average weight of piglets in the age group.

Table 9 Inputs into the beef and dairy cattle units and manure (nitrogen) excretion

Cattle type and groups	Weight [kg]	Water consumption [l/day] ^a	Feed ration (dry matter) [kg/day] ^b	Bedding [kg straw/month] ^{b,c}	Nitrogen excreted [kg N/month] ^d
<i>Beef cattle</i>					
Cows	650	55	10	54	5
Bulls	1000	38	10	54	4
Young stock < 1 year	180–200	14	5	27	2.8
Young stock 1 to 2 years	400	38	6.5	54	4
Young stock > 2 years	540–580	38–45	9	54	4
<i>Dairy cattle</i>					
Cows-in-milk	550	75	10	54	6.4
Dry cows	550	41	10	54	5
Young stock < 1 year	140 - 180	14	5	27	3
Young stock 1 to 2 years	400	25	6.5	54	5
Young stock > 2 years	500	25	9	54	5

^a Source: Swistock (2009).

^b Feed and bedding inputs only apply to the housing period.

^c Assuming that calves require half of cows' bedding requirements.

^d Source: DEFRA (2009a).

2.3.7 Dairy cattle husbandry unit

A dairy herd of between 150 and 180 Ayrshire cows and 70 to 95 young stock are reared at the farm. The herd is classified into six groups: cows-in-milk, dry cows, barren cows, calves younger than one year, heifers between one and two years old and heifers older than two years (see Table S9 in SI). The farm has a year round calving pattern. However, there are more cows in calving in September to February and less at other times. Like the beef cattle, the dairy herd also stays indoors during the winter and outdoors in the summer. They also graze various land plots so that the land classified as 'pasture' has been allocated to the herd on the basis of the number of livestock units, in the same way as for the beef cattle.

The inventory data are summarised in Table 9. The water and feed consumption have been calculated on the basis of the cattle number, age and weight. In addition to these, the milking parlour requires 30 l of water per cow per day for cleaning and 0.12 kWh of electricity per litre of milk. The cows-in-milk are given the same feed concentrate as the beef cattle (see Table S7 in SI).

The outputs from the dairy cattle unit are milk, dairy stock, spent cows and young stock (one-year old). The male young animals and the surplus female young stock are transferred to the beef cattle unit and accounted for in that unit. The annual and total amounts of the outputs from the dairy unit are listed in Table 7 and Table S9 in the SI.

2.3.8 Slaughterhouse

For the slaughterhouse, the slaughtering process, cooling, washing and cleaning operations have been considered. As shown in Table 10, the data for energy, water and wastewater have been obtained from Blonk Agri-footprint BV (2015), while the detergent quantities have been sourced from EC (2005). Slaughterhouse by-products include hide, blood, fat and bones. Given that these by-products are of low value and require further processing in tanneries and rendering plants, all impacts have been allocated to meat.

Table 10 Inventory data for the slaughterhouse

	Electricity [kWh/kg liveweight]	Natural gas [MJ/kg liveweight]	Water [l/kg liveweight]	Detergent [g/kg liveweight]	Wastewater [l/kg liveweight]
Cattle and sheep	0.109	0.15	2	0.11	2
Pigs	0.106	0.24	2.5	0.58	2.5

2.3.9 GHG emissions from enteric fermentation and manure

The estimates of enteric and manure emissions of GHG are based on the age and weight of animals for each type of the herd reared at the farm. They have been calculated using the IPCC Tier 1 factors for sheep and pigs and Tier 2 factors for dairy and beef cattle (IPCC, 2006), in accordance with PAS 2050 (BSI, 2011). The direct and indirect emissions of methane and N₂O from manure deposition have been calculated for the annual average temperature for the UK's South West region of below 15 °C. The emissions arising from the excreta deposited on the soil while grazing have been allocated entirely to the animals. The emissions arising from dairy and beef cattle manure management (as compost) during the indoors period have been allocated to the animals, whereas the emissions resulting from the application of compost as organic fertiliser have been allocated to the crops. Allocation is discussed in more detail below.

2.3.10 Allocation

The farm is a complex integrated system, whereby land and other resources are shared by and transferred between different activities. Furthermore, several units within the system produce co-products. Consequently, allocation of resources and GHG emissions among different farm activities and co-products is necessary. Following the ISO 14044 standard (ISO, 2006b), the inputs and emissions were first subdivided where possible and then the remainder was allocated on a biophysical basis as recommended in various guidelines (e.g. Audsley *et al.*, 1997; IDF, 2015; FAO, 2016a,b). A number of biophysical approaches have been suggested for agricultural systems, such as nutrient requirements of crops (Martínez-Blanco *et al.*, 2014; FAO, 2016b), nutrient uptake of crops (Tuomisto *et al.*, 2012b), nitrogen mineralisation rate (FAO, 2016b, Martínez-Blanco *et al.*, 2014; Knudsen *et al.*, 2012),

physiological feed requirements of animals (FAO, 2016a; IDF, 2015), protein content (Wiedemann *et al.*, 2015), metabolisable energy content (Brankatschk and Finkbeiner, 2014), etc. The allocation approaches used in this study are summarised in Table 11 and the rationale behind is discussed in the following sections.

Table 11 Allocation methods considered in the base case

Sub-system	Activities and products	Allocation method
Crops	Diesel use for crops	Avoided by using crop-specific data
	Other inputs (seeds, machinery, etc.)	Avoided by using crop-specific data
	N ₂ O emissions from fertiliser application (slurry, manure, cover crops and crop residue)	In proportion to nitrogen availability for plants (mineralisation rate) over the rotation period
	Allocation between grain and cereals	Metabolisable energy content
Livestock	Grazing and forage	Livestock unit (feed requirements)
	Feed (concentrate and silage) and other inputs	Avoided by using animal-specific data
	GHG emissions from excreta and manure management system	Allocated to the producing animals
	Products from dairy unit (milk and beef)	Energy requirement
	Products from sheep unit (lamb, sheep and wool)	Protein content

2.3.10.1 Allocation of N₂O emissions from organic fertilisers during the rotation cycle

In a farm following organic agricultural practices, nitrogen fixing by legumes is the primary source of nitrogen fertiliser and the application of manure produced by the farm's livestock serves the purpose of internal nutrient recycling. Nitrogen is present in organic fertilisers in two main forms: organic and inorganic. Inorganic N is readily available to plants in the forms in which it commonly occurs (mostly ammonium and nitrate), while organic N is mineralised slowly over a period of months to years, through the action of soil microbes, to become potentially available for crop uptake (DEFRA, 2010). Therefore, the allocation of N₂O emissions from cattle slurry and FYM has been carried out based on the nitrogen availability to plants (based on mineralisation rate) over the seven-year rotation cycle. The basis for the allocation for each crop is as follows: firstly plant available nitrogen (PAN) in each year is estimated using data for composition of organic and inorganic nitrogen in slurry and FYM (DEFRA, 2010) and annual mineralisation rates for organic nitrogen over the rotation period (Sullivan, 2008). The allocation factors for each year have been calculated by dividing PAN in each year with total PAN over the seven-year rotation period as detailed in Table 12. Each application of organic fertiliser in a given plot of land is considered as the start of the allocation cycle. However, considering that crop in years 1-6 would benefit from the fertiliser applied in the previous rotation, while the fertiliser applied in years 2-7 would benefit the crops in the next rotation, these effects have been accounted within this rotation assuming similar application of organic fertilisers in the previous rotation. Therefore, in any given year, the total N₂O emissions associated with a given plot of land represent the sum of the emissions allocated over the seven years. Since most of the PAN from crop residue and cover crops is released in the first year (Sullivan and Andrews, 2012; Lynch *et al.*, 2016), all N₂O emissions from crop residues and cover crops have been allocated to the next crop. Alternative methods to allocate N₂O emissions are considered in the sensitivity analysis (see section 3.7).

Table 12 Allocation factors for nitrogen application during the rotation cycle^a

Nitrogen source	Allocation factor [%]						
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Slurry after volatilisation	80	10	5	2	1	1	1
FYM after volatilisation	53	12	12	7	5	5	5
Cover crops and crop residue ^b	100	0	0	0	0	0	0

^a Calculation based on nitrogen applied in year 1.

^b Nitrogen from cover crops and crop residue are allocated to the subsequent crops.

Before the allocation is applied, it is necessary to consider the losses of nitrogen as ammonia (by volatilisation) which in turn vary depending on the manure management system. For slurry and FYM from dairy cattle, the loss factor is 40% (IPCC, 2006). The total amount of nitrogen (N) applied to a given plot of land has been calculated as follows:

N applied = N contained in residues of main crops and cover crops + N in slurry after volatilisation + N in FYM after volatilisation

where:

N contained in residues of main crops and cover crops is calculated for each crop according to IPCC (2006)

N in slurry after volatilisation = 0.6×2 [kg N/t slurry] = 1.2 [kg N/t slurry] (DEFRA, 2009a)

N in FYM after volatilisation: 0.6×5.9 [kg N/t FYM] = 3.5 [kg N/t FYM] (DEFRA, 2009a).

2.3.10.2 Allocation of grazing land and forage to livestock

Table 13 details how the farm management allocates the forage cultivated at the farm to the livestock on the basis of total livestock units. The allocation criteria based on livestock units have been used to allocate the GHG emissions from forage cultivation to the cattle and sheep. As mentioned earlier, pigs are fed exclusively with feed concentrate and hence allocation is not applicable.

Table 13 Allocation of grazing and forage land to livestock based on farm records

Livestock	Group	Livestock unit factor ^a	Allocation factor [%]
Sheep	Lowland ewes	0.17	12.7
	Other sheep (rams, stores)	0.1	0.6
	Ewe lambs	0.1	0.4
Dairy cattle	Dairy cows	1	31.5
Dairy young stock	> 2 years	0.8	2.9
	1 to 2 years	0.6	3.8
	< 1 year	0.4	2.5
Dairy bred beef	< 1 year	0.4	6.1
Beef cattle	Cows	0.6	10.6
	Bulls	0.6	0.5
	> 2 years	0.8	3.1
	1 to 2 years	0.6	14.9
	< 1 year	0.4	7.9

^a Livestock unit factor is a ratio based on the feed requirements of each type of animal at the farm relative to a dairy cow, which is assigned a factor of 1.

Table 14 Biophysical allocation factors for products and co-products [%]

Sub-system	Products and co-product	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Wheat	Wheat grains	66	67	68	66	62	66	66
	Wheat straw	34	33	32	34	38	34	34
Oat	Oat grains	76	82	75	76	72	76	76
	Oat straw	24	18	25	24	28	24	24
Barley	Barley grains	70	81	68	70	62	70	70
	Barley straw	30	19	32	30	38	30	30
Rye	Rye grains	61	68	53	61	64	61	61
	Rye straw	39	32	47	39	36	39	39
Dairy	Milk	92	89	87	88	82	88	80
	Meat & stock	8	11	13	12	18	12	20
Sheep	Lamb	50	55	74	43	42	44	32
	Sheep	28	22	4	39	38	27	49
	Wool	22	23	22	18	20	29	20

2.3.10.3 Allocation of GHG emissions between co-products

Allocation of GHG emissions between the co-products obtained from the various units at the farm (cereals and straw; milk, dairy young stock and dairy stock culls; lamb meat, sheep stock and wool) has been carried out on a biophysical basis. Other allocation approaches based on mass and economic are considered as part of the sensitivity analysis. Table 14 specifies the biophysical allocation factors for the cereals and straw applied in each year over the rotation cycle, based on the metabolisable energy of

cereals and straw as suggested by Brankatschk and Finkbeiner (2014). The metabolisable energy of cereals and straw have been obtained from AHDB (2017).

The outputs of the dairy unit are milk, dairy stock culls, beef and the male young stock transferred to the beef cattle unit. The GHG emissions have been allocated using the biophysical approach as recommended by FAO (2016) and IDF (2015). This approach reflects the causal relationship between the energy content in the feed and the physiological requirements to produce milk and beef. The following equation from IDF (2015) has been used to calculate the allocation factor for milk and meat:

$$\text{Allocation factor for milk} = 1 - 6.04 \times \text{BMR}$$

where BMR is the ratio of liveweight of stock sold or transferred annually to the beef unit to the mass of fat and protein corrected milk (FPCM) produced per year.

Allocation of GHG emissions from the sheep unit is more complex as wool production is mainly determined by requirements for protein, rather than energy, which in turn is a key determinant for milk production. Here, co-production of wool and liveweight (for meat) has been modelled following Wiedemann *et al.* (2015) using the protein mass allocation (PMA) method. The protein content in sheep and lamb liveweight has been assumed at 18% and in greasy wool at 70% (Wiedemann *et al.*, 2015). Allocation is not necessary for beef cattle as beef is the only product from this unit.

Furthermore, all the GHG emissions from the generation and management of manure have been allocated to the management of beef and dairy cattle. This means that manure, used as fertiliser, has a zero GHG emissions for crops; however, the emissions from its application to land are allocated to the crops as detailed in section 2.3.8.

3. Results and discussion

Global warming potential estimated for the whole farm over the rotation period is summarised in Figure 4. As indicated in the figure, the annual impact varies from 1816 to 2372 t CO₂e, with an average value of 2118 t CO₂e/yr. Dairy and beef cattle units are the main contributors, causing 45% and 39% of the impact, respectively. This is mainly due to CH₄ emissions from enteric fermentation and N₂O emissions from the excreta deposition. Crop cultivation is the third most significant contributor with 10%, while the contributions of sheep and pigs are relatively small (6% and <1%, respectively). The GWP of different farm activities and products is discussed in the following sections.

3.1 Crop cultivation

GWP arising from the cultivation of crops over the rotation period is shown in Figure 5; further details can be found in Tables S10 in SI. The results in Figure 5 suggest that rye has the lowest average GWP over the rotation cycle (157 g CO₂e/kg) and beans the highest (692 g CO₂e/kg). The impact from barley and oats is similar, estimated at 350 and 369 g CO₂e/kg, respectively, followed by wheat at 232 g CO₂e/kg. Silage emits 166 g CO₂e/kg and straw 128 g CO₂e/kg.

As can also be seen in Figure 5, there is a wide annual variation in the impact for each crop. For example, the GWP of wheat ranges from 183 g CO₂e/kg in year 2 to 392 g CO₂e/kg in year 7. The variation is even greater for beans: from 525 g CO₂e/kg in year 4 to 1567 g CO₂e/kg in year 6. There are several reasons for these variations, including different amounts of crops planted, the size of the plots used and the related annual production (see Table 5). Furthermore, the yield of beans varied widely, from 0.7 to 2.5 t/ha during the seven-year period. It is also possible that in some seasons the crop was partly ploughed in or not fully harvested. Moreover, compared to the cereals, beans were cultivated on the smallest area throughout the rotation (see Table S11 in SI). Finally, the sequence of planting the crops within the rotation cycle is not necessarily followed in all plots and, in some cases, the same crop was grown for two or three consecutive years in the same plot. Therefore, these results illustrate the importance of considering full rotation cycles for more accurate estimations of GHG emissions of crops (and other agricultural products, as discussed further below).

Figure 4 Global warming potential (GWP) for the whole farm over the rotation period

Figure 5 Global warming potential (GWP) of arable crops and co-products over the rotation cycle
 [GWP for each product obtained by dividing the GWP values in Table S10 by the total amount of crops produced annually and over the full rotation period (Table 5), respectively. GWP for straw represents the average for all cereals.]

The contribution analysis in Figure 6 and Figure S3 in SI indicates that the largest contributors to GWP of crops are N₂O emissions from manure application to the land and the arable operations (diesel used in the farm machinery and grain drying). As mentioned earlier, no GHG emissions are associated with the production of manure because they have been allocated to the rearing of livestock. The contribution of liming and the related CO₂ emissions is also relevant for some crops, in particular for oats and silage, but only in some years as liming is not carried out on an annual basis (see Figure S3). In the case of beans, the contribution of seeds to GHG emissions is significant. This is due to the higher GHG emission factor for bean seeds and a relatively higher amount of seeds used per hectare compared to other crops. For grains, the contribution of machinery varies from 8% (oat) to 15% (wheat).

Figure 6 Contribution of different farming operations to global warming potential of arable crops

[The results refer to the seven-year rotation cycle. Arable operations: GHG emissions from production and use of diesel by farm machinery and for drying of seeds after harvest. Manure application: direct and indirect N_2O emissions from use of FYM and slurry. Liming: CO_2 emissions from application of lime to land. Other nutrients: manufacture and transport of lime and trace minerals. Seeds: cultivation and transport of seeds.]

Figure 7 Global warming potential (GWP) of sheep (including lambs), lamb meat and wool over the rotation cycle

[GWP for each product obtained by dividing the GWP values in Table S12 by the total amount of products produced annually and over the full rotation period (Table 7), respectively.]

3.2 Sheep and lamb husbandry unit

GHG emissions associated with the sheep and lamb husbandry unit are summarised in Figure 7. GWP per kg of liveweight sheep (including lambs) ranges from 5.3–7.9 kg CO_2e , averaging 6.3 kg CO_2e over the rotation cycle. Per kg of lamb meat (carcass), the emissions vary from 12–17.8 kg CO_2e , with an overall average of 14.2 kg CO_2e . The main reason for the variation is the difference in the number of lambs reared per ewe each year. The GWP of wool ranges from 20.8–30.9 kg CO_2e/kg , averaging 24.6 kg CO_2e/kg over the rotation cycle.

CH_4 emissions from enteric fermentation and excreta deposition on land account on average for 73% of the total GWP from this unit, followed by the emissions of N_2O from excreta (19%). The contributions of grazing and feed concentrate are small (6% and 2%, respectively) and that of water is negligible.

3.3 Pig husbandry unit

As indicated in Figure 8, the average GWP over the rotation cycle is estimated at 4.8 kg CO₂e per kg of liveweight pigs and 6.7 kg CO₂ eq. per kg of pork carcass meat. Similar to the other farm units, a wide annual variation in the emissions associated with pig rearing can be seen, from 3.9 kg CO₂e/kg liveweight in year 1 to 6 kg CO₂e in year 5. In a similar manner, the impact per kg of pig meat varies from 5.6–8.5 kg CO₂e. The main reason for this is the annual variation in the number of piglets (see Table S5 in SI).

Two main contributors to the GWP from the pig husbandry unit are the feed concentrate (53%) and N₂O emissions from excreta deposition (27%). Methane emissions from enteric fermentation and manure are responsible for 10% of the total GHG emissions, while the bedding accounts for 9%.

3.4 Beef cattle husbandry unit

The GHG emissions associated with the beef cattle, shown in Figure 9, range from 8.6–10.3 kg CO₂e/kg liveweight and 15.8–18.9 kg CO₂e/kg beef (carcass), with an average of 9.7 and 17.7 kg CO₂e/kg, respectively. The variation is due to the annual variation in the GWP of silage and feed crops as well as the variation in the number of calves reared. CH₄ emissions are the largest contributor to the GWP, with ~40% during winter (indoors period) and ~50% over the summer months (outdoors). This is followed by N₂O emissions in summer (~30%) and silage consumption during winter (~25%). The contribution of milk fed to calves varies over the year from 3% to 11%, reflecting the number of calves in the herd and the calving periods. The grazing land causes up to 7% of the impact during summer.

Figure 8 Global warming potential (GWP) of live pigs and pig meat over the rotation cycle
[GWP for each product obtained by dividing the GWP values in Table S12 by the total amount of products produced annually and over the full rotation period (Table 7), respectively.]

Figure 9 Global warming potential (GWP) of live cattle and beef meat over the rotation cycle
[GWP for each product obtained by dividing the GWP values in Table S12 by the total amount of products produced annually and over the full rotation period (Table 7), respectively.]

Figure 10 Global warming potential (GWP) of milk over the rotation cycle

GWP for milk obtained by dividing the GWP values in Table S12 by the total amount of milk produced annually and over the full rotation period (Table 7), respectively.]

3.5 Dairy cattle unit

The average GWP of milk production is estimated at 1.13 kg CO₂e/l, or 1.08 kg CO₂e/kg when corrected for the fat and protein content (Figure 10). Per litre of milk, the impact over the period ranges from 1.02 to 1.21 kg CO₂e. CH₄ emissions and silage contribute most to the impact during winter (~60%); it is also the largest contributor (~40%) in the summer period, together with the N₂O emissions from excreta. Cows-in-milk have higher CH₄ emissions during spring and summer when they produce the largest volumes of milk, since enteric fermentation depends on the feed intake, which is related to the amount of milk produced.

3.6 Comparison of results with other studies

The GWP estimated in this study is compared in Table 15 to the values found in the literature for organic products. As can be observed, the results in the literature vary widely due to numerous factors, such as different methodologies, allocation, geographical regions, farming practices, etc. Nevertheless, the findings from this study fall broadly within the reported ranges. The best agreement is found for spring barley, silage, pigs and pig meat, beef and milk. The values for the liveweight sheep, lamb meat and cattle are somewhat lower than in the literature while those for the spring beans are closer to the top end of the range reported in other studies. The allocation method is the main reason for the differences in the impact for sheep and lamb meat. In the reported studies, economic allocation was applied to allocate the impact between wool and meat, with only 2% allocated to the wool, while the biophysical allocation method used here allocates about 20% to the wool (Table 12).

The greatest difference in the results between this study and the literature is observed for winter wheat and rye, which have a much lower impact here; however, the ranges for winter and spring wheat compare well (Table 15). No GWP values were found in the literature for oats.

3.7 Sensitivity analysis

The parameters that could potentially affect the results include allocation of N and the related emissions of N₂O over the rotation cycle as well as allocation of GHG emissions among the co-products. Therefore, these two parameters are considered in the sensitivity analysis. In addition to the base case considered so far, five scenarios have been developed for this purpose, with scenarios 1-3 related to the allocation of N and scenarios 4 and 5 to the allocation of GHG emissions among the co-products.

Table 16 summarises the assumptions for scenarios 1-3. In Scenario 1, N (and N₂O emissions) is allocated on the basis of the N requirement of the crops as detailed in a fertiliser manual (DEFRA, 2009b). In Scenario 2, they are equally allocated among the crops over the seven-year rotation period, while in Scenario 3 they are fully allocated to the crop applied and none to the any other crops later in the cycle. The remaining two scenarios consider allocation of GHG emissions among the co-products using a

mass basis (Scenario 4) and economic values (Scenario 5), instead of the biophysical allocation used in the base case (see Table 17). The allocation factors used are detailed in S13-14 in SI.

The results of the sensitivity analysis for all five scenarios are shown in Figure 11 and Figure 12 for crops and animal products, respectively. These are discussed in the next sections.

Table 15 Comparison of global warming potential for different organic agricultural products estimated in this and some other studies

Product	Unit	This study: range (average)	Other studies: range (average)	Source
Winter milling wheat	g CO ₂ e/kg	183–392 (232)	460–790 (625)	DEFRA (2009b), Williams <i>et al.</i> (2006), Ecoinvent (2014)
Spring wheat	g CO ₂ e/kg	–	170–550 (360)	Bos <i>et al.</i> (2014), Agri-BALYSE (2014)
Spring oats	g CO ₂ e/kg	240–543 (369)	–	This study
Winter barley	g CO ₂ e/kg	–	360–390 (375)	Ecoinvent (2014)
Spring barley	g CO ₂ e/kg	269–745 (350)	300–390 (345)	Knudsen <i>et al.</i> (2014)
Spring beans	g CO ₂ e/kg	525–1567 (692)	290–710 (470)	Agri-BALYSE (2014), Bos <i>et al.</i> (2014), Ecoinvent (2014)
Rye	g CO ₂ e/kg	111–199 (157)	350–360 (355)	Ecoinvent (2014)
Silage	g CO ₂ e/kg	113–211 (166)	120–170 (145)	DEFRA (2009b), Bos <i>et al.</i> (2014), Ecoinvent (2014)
Straw	g CO ₂ e/kg	98–154 (128)	60	Ecoinvent (2014)
Sheep (liveweight)	kg CO ₂ e/kg	5.3–7.9 (6.3)	4.6– 14.7 (9.7)	Williams <i>et al.</i> (2006); DEFRA (2009b)
Lamb meat (carcass)	kg CO ₂ e/kg	12–17.8 (14.2)	10.1– 27 (18.6)	Williams <i>et al.</i> (2006); DEFRA (2009b)
Pigs (liveweight)	kg CO ₂ e/kg	4–6.1 (4.8)	2.4–7.6 (5)	Agri-BALYSE (2014), DEFRA (2009b), Dourmad <i>et al.</i> (2014), Basset-Mens and van der Werf (2005), Halberg <i>et al.</i> (2010)
Pig meat (carcass)	kg CO ₂ e/kg	5.6–8.5 (6.7)	4.0–9.9 (6.95)	DEFRA (2009b), Williams <i>et al.</i> (2006), Kool <i>et al.</i> (2009)
Cattle (liveweight)	kg CO ₂ e/kg	8.7–10.4 (9.7)	11.1–23.2 (17.2)	The National Trust (2012), de Vries <i>et al.</i> (2015), Casey and Holden (2006)
Beef meat (carcass)	kg CO ₂ e/kg	15.8–18.9 (17.7)	11.6–32 (21.8)	DEFRA (2009b), Peters <i>et al.</i> (2010), Williams <i>et al.</i> (2006)
Milk	kg CO ₂ e/l milk	1.08–1.28 (1.19)	1.2–1.3 (1.25)	DEFRA (2009b), Williams <i>et al.</i> (2006), Haas <i>et al.</i> (2001), Bos <i>et al.</i> (2014), Kiefer <i>et al.</i> (2014)
	kg CO ₂ e/kg milk	1.05–1.24 (1.16)	1.3–1.6 (1.45)	
	kg CO ₂ e/kg FPCM	1.03–1.22 (1.13)	0.8–1.5 (1.15)	Agri-BALYSE (2014), Bos <i>et al.</i> (2014), Thomassen <i>et al.</i> (2008), Hietala <i>et al.</i> (2015)

Table 16 Scenarios for different allocation of nitrogen

Base case and scenarios	Allocation basis	Details
Base case	N mineralisation	As in Table 12
1	N requirement of crop	Assuming N requirements of crops as per fertiliser manual (see Table S15 in SI)
2	Equally among the crops in rotation over seven years	14.3% each year over 7 years for FYM, slurry, crop residue and cover crops
3	Allocated to the crop applied	FYM and slurry: 100% to the crop applied; crop residue and cover crops: 100% to the subsequent crop

Table 17 Scenarios for mass and economic allocation between the co-products

Base case and scenarios	Allocation basis	Details
Base case	Biophysical	As in Table 12
4	Economic	See allocation factors in Table S13 in SI
5	Mass	See allocation factors in Table S14 in SI

3.7.1 Allocation of N and N₂O emissions (Scenarios 1-3)

As shown in Figure 11, the average GWP of the beans decreases by 50% compared to the base case if all nitrogen and the related N₂O emissions from slurry, manure, cover crops and crop residue are allocated on the basis of crop N requirements (Scenario 1). In this case, there is also a decrease in the average GWP of oats and barley by 10% and 20%, respectively. This in turn leads to a 13% increase in the impact from wheat and 11% from both rye and silage. This is because beans do not need N fertiliser, while oats and barley have lower fertiliser requirements compared to wheat and grass (as detailed in Table S15 in SI). If, on the other hand, N is allocated equally among crops over seven years (Scenario 2), the reduction in the impacts from beans, oat and barley is smaller (3%-13%) compared to the base case. However, the impact from rye goes up by 22% compared to the base case. This is due to rye being the last crop in the rotation cycle (planted in year 7) and having a lower allocation of N in the base case (as detailed in Table 12). In Scenario 3, the impact of silage is higher by 8% while that of all other crops is lower by 5%–10%, with the greatest reduction relative to the base case found for the crops planted later in the rotation cycle.

Allocation of N and N₂O emissions also affects the impact from the livestock and the related products, largely because of the silage and crops used as feed and straw as bedding; thus, the GWP variation pattern is similar to that of silage. However, the effect is less pronounced than for the silage because of the high contribution of CH₄ to the total GWP of sheep and cattle. For milk, beef, lamb and wool, there is an increase of 1%-2% in the GWP in Scenarios 1-3. For pigs, the impact is very slightly lower (0.4%-0.7%) which is due to the straw bedding as they are fed by concentrate rather than by silage.

Therefore, these results highlight the importance of considering N over the rotation cycle and how it affects the interconnected units at a farm. The importance of this has also been pointed out by FAO (2016b). Hence, rather than simplifying the calculation of N₂O emissions by averaging N inputs over the fields in the rotation, and thus ignoring the complexity ruling the physical transfer of nitrogen from one year to the next, this study has explored a way to address this complexity by considering the farm as a whole system over a full rotation cycle. These findings suggest that there is a need to develop guidelines on how to allocate N (and N₂O) emissions in crop rotations as these choices have significant effect on the GWP of crops.

Figure 11 The effect of nitrogen allocation on global warming potential of different farm products

Figure 12 Effects of co-product allocation on GWP on farm products

3.7.2 Allocation of GHG emissions (Scenarios 4 and 5)

The choice of the allocation method for GHG emissions has a considerable effect on the GWP of wheat, oats, barley, rye and straw (Figure 12). Compared to the base case, the impact for these crops is reduced by up to 30% if mass allocation (Scenario-4) is applied instead of the biophysical. Conversely, the GWP of straw increases significantly (by 60%), because the mass allocation factors for straw are much higher than in biophysical allocation (see Table S13 in SI). On the other hand, the economic allocation factors for straw are lower (Table S14); therefore, the GWP of straw is 23% lower in Scenario 5, while the impact of wheat, oats, barley and rye is 8%-17% higher relative to the base case. Beans and silage are not affected because they are not associated with any of the crop co-products.

The choice of the allocation method also has a significant effect on the GWP of lamb, wool and milk. If mass or economic allocation is applied, the GWP of wool is reduced by up to 93% and the impact of milk and lamb increases by up to 15% and 24%, respectively, relative to the base case. Pigs and beef show a relatively lower sensitivity to the allocation of GHG emissions, which are mainly due to the straw used as bedding.

3.8 Improvement opportunities

Organic farms with integrated crop-livestock systems, such as the one considered in this work, already incorporate a range of practices aimed at high nutrient recycling and reduction of environmental impacts. This section discusses further opportunities for reducing GHG emissions from organic agriculture, focusing on the hotspots identified in the study: emissions of N_2O and CH_4 from manure and enteric fermentation as well as CO_2 from combustion of diesel used in farm machinery. The options discussed here are relevant not only to this but to other integrated organic farms.

Emissions of N_2O from manure and the related GWP can be reduced by intercropping, i.e. growing two or more crop species on the same plot of land (Jensen *et al.*, 2015). Intercropping enhances the efficiency of nitrogen utilisation by crops, which in turn reduces its losses to the environment as N_2O . Better utilisation of nitrogen also helps to increase crop yields and reduce land requirements. Furthermore, by growing suitable crops together, intercropping can also aid pest and weed control (Jensen *et al.*, 2015).

Further reductions in N_2O emissions from manure can be achieved by reducing excretion of N by livestock. This can be regulated by modifying the composition of the feed. For example, improved types of pig concentrates are available that reduce N excretion, while at the same time having better feed-to-growth conversion rates (Kool *et al.* 2009). Modifying the feed can also be used to reduce CH_4 emissions from enteric fermentation (Leytem and Dugan, 2014; Knapp *et al.*, 2014). For example, adding whole

cottonseeds to the concentrate improves its digestibility, which in turn reduces generation of CH₄ (Hietala *et al.*, 2015).

Emissions of CH₄ from manure can be reduced by treating it, together with crop residues, in anaerobic digestion (AD). The produced digestate can be used to improve nutrient management, particularly as it converts the organically-bound N in the manure to ammonium form, which is more readily available to crops (Tuomisto *et al.*, 2012a). It also contains residual carbon, phosphorous and trace nutrients. Furthermore, biogas can be used to generate heat or electricity. Previous studies (e.g. Whiting and Azapagic, 2014; Fusi *et al.*, 2016) have shown that utilisation of biogas can lead to significant reductions in GWP and other environmental impacts compared to using fossil fuels. However, care must be taken to minimise ammonia emissions from digestate and the related acidification and eutrophication potentials (Fusi *et al.*, 2016).

Substituting diesel with biodiesel in farm machinery could also help to reduce GWP from integrated organic systems. For example, using rape methyl ester (RME) can decrease the impact by 72% relative to diesel if RME is produced at the farm from rapeseed cultivated as part of crop rotation (Fredriksson *et al.*, 2006; Hansson *et al.*, 2007). However, this leads to an increase in acidification (by 30%) and eutrophication (by a factor of five) compared to diesel. If, on the other hand, Fischer-Tropsch diesel produced from straw is used instead, GWP can be reduced by 94% without increasing acidification and eutrophication (Ahlgren *et al.*, 2008).

4. Conclusions

This study has estimated GWP associated with cultivation of organic arable crops, livestock and their products at a large integrated organic farm in the UK. A seven-year rotation cycle has been considered, starting with clover leys in the first three years and followed in the consecutive years by wheat, oats, beans and barley, and finally rye. The farm rears pigs, sheep, dairy and beef cattle and produces related meat products, milk and wool.

The findings indicate that GWP varies significantly over the rotation cycle, both for the whole farm and the individual products. For the whole farm, it ranges from 1816 to 2372 t CO₂e/yr, averaging at 2118 t CO₂ eq./yr or 2.65 tonnes CO₂e/ha. The main contributors are the dairy and beef cattle, causing 45% and 39% of the impact, respectively. Crop cultivation adds a further 10% and sheep rearing 6%. The pigs herd, which is relatively small in size, contributes less than 1% to the total GWP.

The impact from the individual crops also ranges widely, with the maximum values being between 1.8 and three times higher (rye and beans, respectively) than the minimum over the rotation period. The highest average GWP is found for beans (692 g CO₂e/kg) and the lowest for rye (157 g CO₂e/kg). The average impact over the rotation cycle from barley, oats and wheat is estimated at 350, 369 and 232 g CO₂e/kg, respectively. By comparison, silage and straw have a relatively low GWP (166 and 128 g CO₂e/kg). The major hotspots for the crops are N₂O emissions from manure application and CO₂ emissions from diesel used in the farm machinery.

Similar to the crops, there is a wide annual variation in the GHG emissions associated with the livestock and the related products. The GWP of sheep rearing ranges from 5.3-7.9 kg CO₂e/kg liveweight, averaging 6.3 kg CO₂e over the rotation cycle. Per kg of lamb meat (carcass), the emissions vary from 12-17.8 kg CO₂e, with an overall average of 14.2 kg CO₂e. The average GWP of wool is estimated at 24.6 kg CO₂e/kg. The impact from beef cows is in the range of 8.6-10.3 kg CO₂e/kg liveweight, with the average value of 9.7 kg CO₂e. The consequent CO₂e emissions associated with beef vary from 15.8-18.9 kg per kg of carcass meat, averaging 17.7 kg CO₂e/kg. For pigs, the impact varies from 3.9 to 6 kg CO₂e/kg liveweight and for pig meat from 5.6-8.5 kg CO₂e/kg (average of 6.7 kg CO₂e/kg).

Methane emissions from enteric fermentation and excreta deposition on land are the main contributors to the GWP of beef cattle and sheep, while the feed concentrate is responsible for the impact from pigs. Methane emissions are also the main cause of GWP for milk, which ranges from 1.02-1.21 kg CO₂ e/l, with an overall average of 1.13 kg CO₂ e/l.

The sensitivity analysis shows that the results are affected by assumptions for allocation of N and the related N₂O emissions over the rotation cycle. If all N and the N₂O emissions from slurry manure, cover crops and crop residue are allocated on the basis of crop N requirements, the GWP of oats, barley and beans decreases by 10% (oats) to 50% (beans) compared to the base case (where N is allocated over seven years based on the N mineralisation rate). This in turn increases the impact from wheat, silage and rye by up to 13%. If N is allocated to year 1 in the rotation cycle instead, the average GWP of silage is higher by 8%, while the impact of all other crops is lower by 5%–10%, with the greatest reduction relative to the base case found for the crops planted later in the rotation cycle. The allocation of N also affects the impact from the livestock and their products, with the pattern similar to that of silage, largely because of its use as feed.

The results of the sensitivity analysis also suggest that the allocation method for the crop co-products (grain and straw) has a considerable effect on the GWP of wheat, oats, barley, rye and straw. The impact from these crops reduces by up to 30% if mass allocation is applied instead of the biophysical basis used in the base case. Conversely, the GWP of straw increases by 60%. On the other hand, in the case of economic allocation, the GWP of straw is 23% lower, while the impact of wheat, oats, barley and rye is 8%–17% higher relative to the base case. Similarly, the choice of the allocation method has a significant effect on the GWP of lamb, wool and milk. If mass or economic allocation is applied, the GWP of wool is reduced by up to 93% and the impact of milk and lamb increases by up to 24% compared to the base case.

Therefore, these results highlight the importance of considering integrated farms, such as the one studied here, as whole systems, taking into account a full rotation cycle. This ensures not only that the estimates of environmental impacts are more representative of the complex interconnections between different sub-systems within a farm, but also helps identify the benefits of improvement opportunities at a systems level, in congruence with the principles of integrated organic farming.

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Life cycle greenhouse gas emissions from integrated organic farming: a systems approach considering rotation cycles

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Table S1 Land area and diesel consumption for different field operations

Field operations	Total area covered over the 7-year rotation cycle [ha]	Specific diesel consumption [l/ha]	Source
Broadcasting	118	2.3	Williams <i>et al.</i> (2006)
Combine harvesting	1,788	21.7	Williams <i>et al.</i> (2006)
Drilling	2,417	5.8	Williams <i>et al.</i> (2006)
Drying of grain	1,630	56	Downs and Hansen (1998)
Fertiliser spreading	3,191	12.9	Williams <i>et al.</i> (2006)
Harrow combing	2,220	6.3	Williams <i>et al.</i> (2006)
Hoeing	10	19.4	Williams <i>et al.</i> (2006)
Lime spreading	138	6.5	Williams <i>et al.</i> (2006)
Planting	45	4.7	Frisby (2010)
Ploughing	1,822	19.8	Farm data
Power harrowing	2,254	18.5	Farm data
Pressing	1,821	4.2	Farm data
Rolling	1,188	4.2	Williams <i>et al.</i> (2006)
Rotavating	19	4.2	Frisby (2010)
Spraying manganese	7	1.7	Williams <i>et al.</i> (2006)
Straw baling	5,578	6.4	Williams <i>et al.</i> (2006)
Straw cutting/mowing	3,920	34	Williams <i>et al.</i> (2006)
Terradisc	2,345	4.2	Frisby (2010)
Undersowing	72	4.9	Bentley-Fox (2004)
Whole crop harvesting	21	10.9	Dyer and Desjardin (2003)
Bale handling (tonne)	6048	1.3 l/tonne	Dalgard <i>et al.</i> (2001)
Internal product movement (tonne)	24,870	0.3 l/tonne	Ecoinvent (2010)

Table S2 Correction factors for diesel consumption in field operations over the rotation cycle

Diesel consumption	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Theoretical consumption [l]	45,941	46,993	52,583	52,842	57,467	58,118	58,180
Actual consumption [l]	40,103	41,618	40,460	40,865	51,702	53,229	56,435
Correction factor	0.87	0.89	0.77	0.77	0.90	0.92	0.97

Table S3 Composition of feed concentrate for ewes

Ingredient	Concentration ^a [%]
Organic Barley	50
Organic maize	20
Organic sugar beet pulp	12
Organic soybean meal	15
Vitamins and minerals	3

^a Estimated GHG for feed for ewes = 0.6 kg CO₂e./kg

Table S4 Sheep and lambs herd size over the rotation cycle

Sheep	Average liveweight [kg]	Number of heads						
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Ewes (breeding sheep)	60	483	401	361	303	382	429	430
Rams (breeding sheep)	80	17	13	17	16	11	12	15
Lambs (<1 year)	20	254	261	322	343	319	304	287
Other sheep (> 1 year)	50	24	21	33	3	23	5	0
Ewes sold	60	114	70	8	119	127	71	177
Rams sold	80	7	4	4	3	10	5	22
Lambs sold	20	654	566	719	413	462	378	404

Table S5 Composition of pigs feed concentrate (Martins *et al.*, 2002)

Component	Feed for piglets ^a	Feed for adult pigs ^b
	[%]	[%]
Organic wheat	21.8	21.1
Organic barley	15.8	19.3
Organic peas	10.8	15.0
Organic rape expeller	10.0	12.5
Organic oats	11.9	11.6
Organic triticale	10.0	5.0
Wheat feed		4.8
Organic soya expeller	13.4	3.1
Organic molasses		3.0
Organic beans	4.2	2.0
Vitamins and minerals	1.0	1.4
CaCO ₃ (limestone)	0.7	0.9
Organic soya oil		0.4
Dicalcium phosphate	0.5	
Total	100	100

^a Estimated GHG for feed for piglets = 0.63 kg CO₂e/kg

^b Estimated GHG for feed for adult pigs = 0.57 kg CO₂e/kg

Table S6 Pigs herd size over the rotation cycle

Pigs	Average liveweight [kg]	Number of heads						
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Sows	225	5	6	6	8	9	6	5
Boars	250	1	1	1	2	2	2	2
Weaners	18	18	22	15	15	28	26	12
Growers	30	18	22	15	15	50	26	12
Sows sold	225				1	1	4	
Growers sold	35	74	51	91	49	62	102	51

Table S7 Composition of feed concentrate for cows-in-milk

Ingredient	Concentration ^a
	[%]
Organic barley	31
Organic sunflower	26
Organic oats	20
Organic lucerne	15
Organic maize	5
Calcium carbonate	1
Sodium chloride	1
Magnesium dicalcium phosphate	1

^a Estimated GHG for feed for cows = 0.8 kg CO₂e/kg

Table S8 Beef cattle herd size over the rotation cycle

Beef cattle	Average liveweight [kg]	Number of heads						
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Cows	650	90	85	87	88	81	125	109
Male < 1 year	200	45	51	34	40	45	95	59
Heifer < 1 year	180	44	42	38	40	42	95	58
Male 1 to 2 years	400	58	64	76	67	72	60	84
Heifer 1 to 2 years	400	50	56	61	66	58	68	91
Male > 2 years	580	6	3	12	10	13	15	13
Heifer > 2 years	540	4	2	9	6	6	13	24
Bulls	1000	4	4	3	3	4	8	6
Beef cattle sold	550	131	112	130	137	159	206	191

Table S9 Dairy cattle herd size over the rotation cycle

Dairy cattle	Number of heads						
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Cows-in-milk	115	131	142	138	146	134	125
Dry cows	35	34	40	42	42	42	44
Barren cows	2	3	1	1	1	0	0
Young stock < 1 year	32	39	33	34	35	32	31
Young stock 1 to 2 years	31	34	37	35	37	34	26
Young stock > 2 years	15	16	20	22	20	24	27
Young stock male to beef (< 1 year)	30	40	30	45	44	36	57
Young stock female to beef (< 1 year)	20	29	24	36	43	44	39
Dairy cattle sold	18	26	32	32	41	28	47

Table S10 Annual and total global warming potential (GWP) of arable crops over the rotation cycle

Crop	Annual GWP [t CO ₂ -eq./yr]							Full rotation cycle [t CO ₂ -eq.]
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	
Winter wheat grains	47.4	68.9	91.0	66.9	61.3	63.8	39.2	438.6
Spring oat grains	86.7	73.3	174.2	95.1	133.2	127.0	91.1	780.7
Spring barley grains	28.3	48.4	25.8	29.3	44.5	43.2	54.8	274.4
Spring beans	14.0	28.2	10.5	18.4	45.4	26.6	6.5	149.5
Rye	16.9	22.2	5.5	9.7	9.7	9.6	14.4	88.0
Straw (all crops)	74.4	71.0	116.5	83.0	120.6	97.2	81.5	644.1
Silage	185.7	177.3	239.5	194.5	283.2	289.7	296.2	1,666.1

Table S11 Land area used for different crops

Crops	Area (ha)						
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Wheat	82	86	106	100	77	75	41
Oats	86	72	101	91	89	79	79
Barley	31	47	37	36	49	47	60
Beans	10	26	9	16	44	24	6
Rye	30	32	14	16	19	20	27

Table S12 Annual and total global warming potential (GWP) of animals and their products over the rotation cycle

	Annual GWP [t CO ₂ -eq./yr]							Full rotation cycle [t CO ₂ -eq.]
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	
Sheep and lamb	115.2	103.4	103.7	93.8	107.8	97.0	109.3	730.2
Wool	31.7	30.5	28.8	21.2	27.2	39.7	26.8	205.9
Pigs	10.4	10.7	14.0	11.4	16.0	16.6	9.9	88.8
Beef cattle	675.9	636.7	725.3	759.4	865.4	1041.6	1056.4	5760.8
Dairy cows	46.3	50.5	53.9	55.1	54.9	54.5	35.4	350.6
Milk	786.5	788.1	925.7	917.2	906.3	909.7	913.9	6147.3

Table S13 Mass allocation for the factors for products and co-products [%]

Sub-system	Products and co-product	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Wheat	Wheat grains	46	47	48	46	42	46	46
	Wheat straw	54	53	52	54	58	54	54
Oat	Oat grains	61	70	60	61	56	61	61
	Oat straw	39	30	40	39	44	39	39
Barley	Barley grains	51	66	49	51	43	51	51
	Barley straw	49	34	51	49	57	49	49
Rye	Rye grains	41	49	34	41	44	41	41
	Rye straw	59	51	66	59	56	59	59
Dairy	Milk	98.6	98.3	97.9	98.0	97.1	98.0	96.8
	Meat & stock	1.4	1.7	2.1	2.0	2.9	2.0	3.2
Sheep	Lamb & sheep	93	93	93	95	94	90	94
	Wool	7	7	7	5	6	10	6

Table S14 Economic allocation factors for products and co-products^a [%]

Sub-system	Products and co-product	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Wheat	Wheat grains	74	75	76	74	71	74	74
	Wheat straw	26	25	24	26	29	26	26
Oat	Oat grains	82	87	81	82	79	82	82
	Oat straw	18	13	19	18	21	18	18
Barley	Barley grains	77	86	76	77	71	77	77
	Barley straw	23	14	24	23	29	23	23
Rye	Rye grains	67	74	60	67	70	67	67
	Rye straw	33	26	40	33	30	33	33
Dairy	Milk	95.8	92.4	95.6	96.1	95.7	93.6	91.3
	Meat & stock	4.2	7.6	4.4	3.9	4.3	6.4	8.7
Sheep	Lamb & sheep	98.4	98.2	99.4	97.0	98.7	98.8	99.1
	Wool	1.6	1.8	0.6	3.0	1.3	1.2	0.9

^a Prices for the cereals and straw are from Lampkin et al. (2008). The economic factors for the dairy and sheep units are based on the farm revenue data.

Table S15 Fertiliser requirements of different crops (DEFRA, 2010)

Crop	N requirements (kg/ha)
Wheat	220
Oat	120
Barley	140
Rye	120
Beans	0
Grass	200

Figure S1 Sheep and lambs herd size and lamb sales over the rotation cycle [no. of heads]

Figure S2 Pigs herd size over the rotation cycle [no. of heads]

■ Arable operations ■ Grain drying ■ Manure application ■ Liming ■ Other nutrients ■ Seeds ■ Machinery

Winter wheat

Spring oats

Barley

Beans

Rye

Silage

Whole farm (all crops)

Figure S3 Contribution of different farming operations to global warming potential of crops

[Grain drying: drying using heated air. Seeds: cultivation and transport of seeds; Other nutrients: manufacture and transport of lime and trace minerals. Lime application (CO₂ emissions): emissions from the application of lime to the soil; Manure application (N₂O emissions): direct and indirect N₂O emissions from the application of manure. Arable operations: use of machinery and drying of seeds after harvest.].

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