REFEREED ARTICLE

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Options from life-cycle analysis for reducing greenhouse gas emissions from crop and livestock production systems

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ABSTRACT

Options for reducing greenhouse gas emissions (GHGE), measured as global warming potential, in twelve crop and seven livestock systems were explored using a systems model-based life-cycle analysis of environmental burdens and resource use. Differences between crops in GHGE per kg product reflected differences in yield per hectare. Technological changes found to reduce GHGE per kg of crop were: (i) 20% decrease in total N (all crops except legumes); (ii) no-till (cereals and legumes only) and (iii) no straw incorporation (cereals and rape). Reductions in GHGE ranged from 2% (sugar beet) to 15% (cereals). GHGE per kg crop were also reduced by increasing crop yields by 20%. The maximum potential to reduce livestock GHGE was estimated by identifying for each livestock sector the system which gave the greatest reduction in GHGE per kg of product. Alternative systems were associated with reductions in GHGE of between 7% (beef from the dairy herd) and 21% (sheep meat). Nitrogen use efficiency (NUE) ranged from 48% for oilseed rape to 85% for sugar beet, and from 5.8% for sheep meat to 33% for poultry meat production. The results indicate that improvements in productivity and efficiency of resource use result in lower GHGE per unit of product and increased NUE.

KEYWORDS: Life-cycle analysis; resource use; greenhouse gases; crops; livestock

1. Introduction

Governments have made international commitments to reduce greenhouse gas emissions (GHGE) and the United Kingdom government has set a target of an 80% reduction in emissions of GHGE by the year 2050 compared to the baseline of 1990 (Office of Public Sector Information, 2011). Reductions in GHGE in food production largely involve reducing emissions of nitrous oxide from agricultural soils and manures, and emissions of methane from enteric fermentation and livestock manures (IPCC, 2006).

Total GHGE from UK agriculture are estimated to have decreased by 21% in the period 1990 to 2009 (DEFRA, 2011). Although some progress has been made towards the achievement of the UK government's target, the decrease in GHGE has been driven by reduced amounts of fertiliser nitrogen applied per hectare of land and by reductions in the populations of dairy cattle and sheep (DEFRA, 2011). Other factors, such as improvements in efficiency of resource use, are not currently captured in the national inventory (MacCarthy et al., 2011). In future decades, the rising world human population will increase the pressure to produce more edible food crops from finite areas of cultivatable land (Godfray et al., 2010). The ability of ruminant livestock to convert grasslands and forage crops into human-edible food of high biological value will continue to make a significant contribution to higher total food output. The challenge is to produce more food with lower GHGE per unit of product, focussing attention on more efficient use of agronomic resources in crop production, on increased efficiency of breeding females in livestock production, and on improved efficiency of feed use in all systems of milk and meat production. Technological options to achieve these objectives need to be explored at the individual system level, to support the activities of farmers, by examining systems through life-cycle analysis in which the GHGE attributed to each component is assessed in a fully authenticated methodology (Williams, 2006). In this way, the impact of variations in management strategies can be quantified theoretically.

Previous research has concentrated on determining the environmental burdens of existing systems of food production (Williams et al., 2006; Ledgard et al., 2010; Nemecek et al., 2008). In this paper we have taken the work a stage further to assess the effects on GHGE, of implementing theoretically a range of technological options in conventional systems of crop and livestock production operated on farms in northern Europe and America, with the objective of determining the potential reductions in GHGE which might be feasible in each system without reducing the total production of food or changing the national diet. Other studies have considered the scope from making changes to the national diet

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(Audsley et al., 2009). Organic options are not considered here because they have been explored elsewhere (e.g. Olesen et al., 2006; Williams et al., 2006; Weiske and Michel, 2007). Given the importance of nitrous oxide emissions from agricultural soils as a source of non-CO_2 GHGE (MacCarthy et al., 2011), the potential effects of alternative options on NUE (N in product as a percentage of total N input) are also explored.

2. Material and methods

Typical northern European crop and livestock production systems were studied using the Cranfield system model-based life-cycle analysis (LCA, Williams et al., 2006), available online at www.agrilca.com. LCA is a holistic analysis and the methodology specifically includes GHGE not only from the farm, but also from industries that produce inputs such as fertiliser, feeds, machinery and fuel, including overseas production and by-products. Critically, burdens are expressed in terms of the functional unit, in this case per kg of product fresh weight, per MJ of edible energy or per kg edible protein at the farm gate, not the GHGE of whole farms. This approach focuses attention on options linked to both technical and financial efficiency (Evans, 2009). GHGE are expressed as a global warming potential (GWP_{100}) in tonnes CO_2 equivalent (CO_2e) per unit of product, using a 100 year time frame and the GWP values for gases from the Intergovernmental Panel on Climate Change (IPCC, 2006). The methods and data inputs to the LCA model have been described in detail for the production of bread wheat, oilseed rape and potatoes in England and Wales by Williams et al. (2010).

The production systems studied in the Cranfield LCA represent all the main methods of producing each commodity such as for example for wheat: organic, conventional, ploughed, reduced tillage, direct drill; for pigs: indoor or outdoor sows or weaners, light or heavy pigs; for beef, suckler or dairy-bred calves, intensive cereal, extensive grass, upland or lowland, spring or winter calving. The systems modelling approach includes equations defining the interactions between yield-fertiliser-crop N-long term soil N and leaching, yield-feed energy-manure-crop response, as well as the effect of different soil type and rainfall across the UK. This approach calculates the impact of changes within the farm system, for example a decrease in fertiliser input reduces crop yield per hectare and crop nitrogen content and long-term soil nitrogen (Williams et al, 2010). Equally, an increase in the crop yield from plant breeding (with no reduction in crop N content) requires additional fertiliser input.

For each system emissions of nitrous oxide (N_2O) were calculated using the IPCC Tier 1 methodology (IPCC, 2006). Other emissions such as those from energy use, from manure storage and use, or nitrate leaching were calculated systematically by considering each aspect of the system in turn. A calculated change in GHGE therefore represents the total effect of a change in the farming system. The output of each system is defined as the product at the farm gate – grain, seed, forage, whole milk, whole eggs or meat bone-in carcase weight. Two major crops grown in America – soya beans and maize grain were included for comparison with UK cropping systems. The current combination of systems and their emissions were considered as baseline (2005) values for agricultural GHGE.

Based on analyses of the impact on GHGE of making changes to the systems, alternative technological options for each production system were developed in the present study using Release 3 Version 48 of the model (July 2009). Percentage reductions in GHGE for the alternative options were expressed relative to the values for 2005 for the typical systems. The GHGE from post farm gate processing of crops and livestock products are not included in this analysis.

Ten UK and two American cropping systems were included in the present study to cover the range of major agricultural food crops except rice, the range in soil types, and a range of contrasting agronomic practices. Typical cropping systems were defined in relation to soil texture, soil cultivation technique, straw incorporation, irrigation, and the average total input of nitrogen (N) per hectare (Table 1). The analysis determined the new long-term steady state for the soil, but as the soil was in steady state, no contribution was assumed for changes in the concentration of soil carbon and the proportion of soil types nationally (Table 1) was unchanged. The typical composition of each crop product in terms of concentration of dry matter, energy and crude protein is shown in Table 2.

Alternative cropping management options were studied in the model by varying three major characteristics described for each system in Table 1: Type of cultivation (ploughing versus no-till or direct drilling), straw incorporation (zero versus 100%) and level of fertiliser N. Stepwise reductions in total N input were analysed to determine an appropriate level which might reduce GHGE by more than crop yields to give a net environmental benefit per unit of crop produced. Irrigation (zero versus 100%) was studied for potatoes alone. The effect on GHGE of a theoretical increase in crop yield of 20% compared to current average yield (Table 4) was also explored.

The LCA model considers the full range of alternative livestock rearing systems; high and low intensity, spring and autumn calving, indoor and outdoor, hill, upland and lowland. Typical details of European livestock systems are described in Table 3, comprising milk production from autumn-calving dairy cows housed for six months of the year, semi-intensive beef from calves born in dairy herds, spring-calving suckler beef production, sheep meat production from crossbred ewes, indoor heavy bacon production, poultry meat from housed broiler chickens, and egg production from housed layers. Inputs of concentrate and forage DM refer to the complete system and include both the dam and her offspring. Emissions associated with imported feeds and fertilisers were calculated in the inventories of the country of origin and were included in the analysis. No account was made of post-farm gate GHGE, such as energy use in the processing of milk and carcases, and in product packaging and distribution.

The range of options available to reduce livestock GHG was discussed by Gill et al. (2009), who identified improved fertility, health and genetics as the major factors contributing to decreasing the number of

Table 1: Typical values for soil composition, cultivation and nitrogen input for crop systems (from Williams et al., 2006)

Crop	Soil type (%)			Cultivations (%)			Straw incorporation (%)	Irrigation (%)	Total N (kg/ha)	Type of N fertilizer (% of total)	
	Clay	Loam	Sand	Plough	Reduced tillage	No-till				Ammonium nitrate	Urea
Winter bread wheat	34	48	18	57	41	2	75	0	219	80	20
Winter feed wheat	34	48	18	57	41	2	75	0	204	82	18
Winter barley	22	54	24	57	41	2	15	0	163	82	18
Spring barley	9	75	16	57	41	2	0	0	123	82	18
Winter oilseed rape	43	29	28	50	45	5	100	0	204	69	31
Sugar beet	7	82	12	100	0	0	–	0	122	96	4
Main-crop potatoes	7	82	12	100	0	0	–	56	191	96	4
Second-early potatoes	7	82	12	100	0	0	–	48	171	96	4
Field beans	39	33	28	57	43	0	100	0	0	–	–
Soya beans[1]	30	28	42	27	53	20	–	0	0	–	–
Maize grain[1]	30	28	42	30	58	12	100	0	134	90	10
Forage maize	55	16	29	57	41	2	0	0	212[2]	90	10

[1]America. [2]A significant proportion of the total N input to forage maize is from manure, but the reduction in fertiliser use is credited to the animal and not to the crop. The same principle applies to the other crops but to a lesser extent.

animals required per kg of product. In addition, feeding strategies to reduce methane and nitrous oxide emissions were considered to be particularly valuable in terms of increasing efficiency of livestock systems. The conversion of human-edible and inedible animal feeds into animal products has been reviewed elsewhere (Wilkinson, 2011) and is not considered here.

Alternative systems in terms of reduced GHGE compared to the equivalent typical system were explored, using the Cranfield model, for each livestock sector by varying those system components associated with technological efficiency, described above, which were considered most likely to reduce GHGE (e.g. fecundity, longevity, feed conversion ratio). Alternative systems were defined using the model with the most extreme feasible improvement in each factor in order to estimate the maximum potential for reducing GHGE.

3. Results and discussion

Crops

Fresh weight yields for the typical cropping systems and for the options to reduce GHGE are shown in Table 4. The options found to reduce GHGE also reduced crop yields but to a relatively small extent ranging from 5% or less for potatoes, field beans, soya beans and forage maize to between 7 and 11% for the other crops.

Typical GHGE, expressed as tonnes CO_2e/tonne product fresh weight at the farm gate are shown in Table 5. The range in GHGE between crops was considerable, with oilseed rape and sugar beet having the highest and lowest emissions per tonne of crop fresh weight, respectively. Standardising potato and sugar beet yields to 860 g DM/kg fresh weight to make them comparable with the cereal crops produced values of 0.59, 0.44 and 0.20 kg CO_2e kg^{-1} for main-crop potatoes, second early potatoes and sugar beet, respectively. Forage maize had the lowest GHGE per kg of the cereal crops because, being harvested in its entirety, it had a substantially higher yield per hectare than the other crops, though of lower quality (Table 2).

No-till or direct drilling (cereals and legumes) reduced GHGE. Although no-till was associated with reduced crop yield compared with ploughing (Table 4), there was a reduction in GHGE, mainly as a result of lower primary energy use. The restrictions of applying the IPCC Tier 1 emission factors meant that the model assumed there were no changes in soil N_2O emissions for different cultivation techniques. However there may be an increase in N_2O compared to the typical system which comprised ploughing and reduced tillage in approximately equal proportions because of increased soil anaerobic conditions (Robertson et al., 2000). The extent to which any increase in N_2O emissions might offset the reduction in primary energy use is not known. The reductions in GHGE due to no-till alone ranged from 0.01 kg CO_2e kg^{-1} for wheat and maize (a 2% reduction) to 0.07 kg CO_2e kg^{-1} (10% reduction) for soya beans. An exception was oilseed rape where the change to 100% no-till was associated with an increase in GHGE of 0.04 kg CO_2e kg^{-1} because the relatively high yield penalty (13%) outweighed the saving on primary energy. No-till was therefore excluded as an agronomic option for oilseed rape. The typical proportion

Table 2: Typical concentrations of dry matter, metabolisable energy and crude protein in crop products (from Thomas, 2004 and Williams et al., 2006)

Crop	Dry matter (DM) ($g\ kg^{-1}$ fresh weight)	Metabolisable energy (ME) ($MJ\ kg^{-1}$ dry matter)	Crude protein (CP) ($g\ kg^{-1}$ dry matter)
Winter bread wheat grain	860	13.6	130
Winter feed wheat grain	860	13.6	116
Winter barley grain	860	13.2	123
Spring barley grain	860	13.2	116
Winter oilseed rape seed	930	23.1	212
Sugar beet roots	220	13.2	31
Main-crop potatoes	200	13.3	93
Second-early potatoes	200	13.3	93
Field bean seed	860	13.3	298
Soya bean seed	860	14.5	415
Maize grain	860	13.8	102
Forage maize (whole plant)	280	11.0	101

of no-till in America for soya bean and maize grain production was markedly higher than in the UK (Table 1), reflecting lighter soils and the need to preserve soil moisture.

Not incorporating straw reduced GHGE. The main source of GHGE due to incorporating straw into soil is N_2O emission from soil during the winter. No use was assumed for the straw made available by not incorporating it into the soil. The GHGE associated with the removal of straw (baling and transport) are assumed to be an environmental burden associated with the use of straw as a product of cereal grain production, not with the production of grain itself. If the straw were to be used to replace other sources of energy this would mitigate the GHG burden of its production and disposal as a waste product of cereal grain production. The model determines the long-term steady state system for all processes. This includes nitrogen from the rotation, nitrate leaching and soil organic matter. Thus incorporating or not incorporating straw continues for a long time, so that the soil is in steady state. There is thus no contribution from the change in the soil organic matter. In the transition period of not incorporating, soil organic matter would be reduced giving a release of CO_2 which the benefit of reduced N2O would take some years to counteract, and *vice-versa*. The magnitude of the effect of a change away from straw incorporation depended on the typical proportion of straw incorporated for each crop (Table 1). Reductions in GHGE due to no straw incorporation alone were zero, 0.01 (2% reduction), 0.04 (8%) and 0.06 kg CO_2e kg^{-1} (2%) for spring barley, winter barley, wheat, and oilseed rape, respectively (Table 4).

Irrigation of main-crop potatoes was associated with a progressive reduction in GHGE, from 0.14 kg CO_2e kg^{-1} without irrigation to 0.13 kg CO_2e kg^{-1} with 100% irrigation – a 6% decrease. As the majority of potato crops are either irrigated or do not need irrigation, the overall potential reduction in GHGE is probably only about 1%.

A reduction in the total quantity of N input was associated with decreased primary energy use and reduced emissions of N_2O since under the Tier 1 IPCC methodology the emission factor for N_2O was a fixed percentage (1%) of total N applied (IPCC, 2006). Progressive decreases in total N not only reduced crop yields and soil nitrate concentrations but also reduced emissions of ammonia. However, small reductions in N were reflected in relatively small decreases in crop yield which were more than compensated by greater reductions in N_2O emissions and by reductions in primary energy use in the production of the fertiliser in the first place. An average reduction of 20% in total N input was found to produce a net GHGE benefit for all crops and was therefore considered to be the most appropriate option (Table 5). Kindred et al. (2008) found a similar optimal reduction in fertiliser N input to UK wheat of 43 kg ha^{-1} (a 22.5% reduction) to minimise GHGE,

Table 3: Main components of typical livestock systems (from Williams et al., 2006)

Sector	Milk	Dairy beef	Suckler beef	Sheep meat	Pig meat	Poultry meat	Eggs
Days housed	190	180	182	0	126	42	385
Concentrates (kg DM)	2047	960	579	76[5]	366	4.9	52
Forage[1] (kg DM)	6792	2281	4982	1018	–	–	–
Live weight gain (kg/day)	–	0.90	0.88	0.17	0.56	0.06	–
Output (kg/year)	7850	285	232[3]	60[6]	–	–	14.8[8]
Live weight at slaughter (kg)	–	565	565	41	109	2.4	–
Age at slaughter (months)	–	19	20	7 to10	6.3	1.5	–
Feed conversion ratio (kg feed DM/kg milk or live weight gain)	1.13[2]	6.23[4]	10.7[4]	18.2[7]	2.89	1.76	3.06[9]
Longevity of breeding females (years)	3.2	–	7	4.2	2.5	–	1.1
Manure as slurry (%)	88	18	0	0	35	0	25[10]

[1]Grazing and conserved forage. [2] kg total feed DM/kg milk. [3] Live weight of calf at weaning. [4] kg total feed DM/kg total live weight gain (slaughter weight minus 45 kg birth weight). [5] Includes concentrates for finishing store lambs. [6] Per ewe. [7]kg total feed DM/kg output. [8] 295 eggs/layer, 50g/egg. [9]kg feed/kg eggs. [10] Proportion with belt-cleaned cages, remainder on deep cages.

Table 4: Predicted yields for typical crop systems and for agronomic options to reduce greenhouse gas emissions

Crop	Typical yield[1]	Predicted yield with agronomic options[2] to reduce GHGE	Reduction in yield (%)
	(tonnes fresh weight ha^{-1})		
Winter bread wheat	7.7	7.0	9
Winter feed wheat	8.1	7.2	11
Winter barley	6.5	5.9	9
Spring barley	5.7	5.2	9
Winter oilseed rape	3.2	2.9	9
Sugar beet	63.0	58.1	8
Main-crop potatoes	52.0	49.6	5
Second-early potatoes	48.0	46.1	4
Field beans	3.4	3.3	4
Soya beans	2.4	2.3	2
Maize grain	7.2	6.7	7
Forage maize	11.2[3]	10.8[3]	4

[1]Systems as described in Table 1. [2] See text for details of options. [3] tonnes dry matter ha^{-1}

after accounting for land-use change to maintain grain output.

An effect of reducing total N input is that the concentration of N in the crop is also reduced (Rothamsted Research, 2006). This reduces the likelihood of bread wheat grain being of a suitable quality for bread-making and thus a greater proportion is assumed to be only suitable for animal feed. Alternatively, a switch to a variety with a higher inherent protein content might be feasible, but these varieties are lower-yielding (HGCA, 2011) and thus GHGE per kg product would be similar. Reduced concentrations of N are unlikely to be consequential in the case of potatoes and sugar beet as it is not a quality criterion in these crop products. The decreases in GHGE due to reduced N input (Table 5) were relatively small for sugar beet and potatoes (2 to 3% reduction), but were of greater significance for the cereal crops and oilseed rape: 0.03 kg CO_2e kg^{-1} (7 to 8% reduction) for feed wheat and barley, 0.04kg CO_2e kg^{-1} for bread wheat (7%) and forage maize (13%), and 0.05 kg CO_2e kg^{-1} for oilseed rape (5%) and maize grain (11% reduction).

Where all three agronomic options were appropriate to the crop, reduced N had the greatest effect on GHGE (Table 5). The combined effect of the options on the percentage reduction in GHGE was lowest for sugar beet (2%) and highest for the cereal crops (average 15% reduction). The percentage reduction in GHGE was similar for the two potato crops (3%), and was also similar for the two grain legumes (9%).

Typical yields per hectare of metabolisable energy (ME), crude protein (CP) and GHGE per unit of ME and CP are in Table 6. Yields of ME were low for the two legume crops, but they contained more CP per kg DM than other crops (Table 2) and yields of CP for field beans and soybeans were comparable with those of wheat. Forage maize yields of both ME and CP were relatively high reflecting the fact that this crop is harvested in its entirety for livestock feed. GHGE per MJ of ME generally reflected yield of ME, ranging from 0.015 for sugar beet to 0.056 for soya beans. GHGE per kg CP were higher than average for potatoes and sugar beet and lower than average for field and soya beans and forage maize.

The output of the major grain crops has increased steadily over the years and there is undoubtedly scope for them to be increased further - for example through improved plant breeding and crop health (see review by Godfray et al., 2010). GHGE per kg product were

Table 5: Greenhouse gas emissions (GHGE) from typical crop systems and from options to reduce GHGE

Crop	Typical system	No-till	No-till + no straw incorporation	No-till + no straw incorporation + 20% reduced N	20% increase in crop yield per hectare
	GHGE (kg CO_2e kg^{-1} product fresh weight)				
Winter bread wheat	0.51	0.50	0.46	0.42	0.48
Winter feed wheat	0.46	0.45	0.41	0.38	0.43
Winter barley	0.42	0.40	0.39	0.36	0.39
Spring barley	0.38	0.35	–	0.32	0.36
Winter oilseed rape	1.05	–	1.03	0.97	0.95
Sugar beet	0.043	–	–	0.04	0.04
Main-crop potatoes[1]	0.14	–	–	0.13	0.13
Second-early potatoes[2]	0.10	–	–	0.10	0.09
Field beans	0.51	0.46	–	0.46	0.46
Soya beans	0.70	0.64	–	0.64	0.61
Maize grain	0.38	0.37	–	0.33	0.36
Forage maize	0.30	0.29	–	0.26	0.29

[1]Cool-stored until May: weighted cooling energy applied. [2] No storage.

Table 6: Typical yields of metabolisable energy (ME) and crude protein (CP) and GHGE per unit of ME and CP from crops

Crop	Yield		GHGE	
	ME (GJ ha^{-1})	CP (kg ha^{-1})	kg CO_2e MJ^{-1} ME	kg CO_2e kg^{-1} CP
Winter bread wheat	90	859	0.044	4.56
Winter feed wheat	94	803	0.039	4.61
Winter barley	74	687	0.037	3.97
Spring barley	65	570	0.033	3.81
Winter oilseed rape	69	631	0.049	5.33
Sugar beet	183	434	0.015	6.24
Main-crop potatoes	138	967	0.053	7.53
Second-early potatoes	128	893	0.038	5.38
Field beans	39	882	0.045	1.99
Soya beans	30	867	0.056	1.96
Maize grain	85	632	0.032	4.33
Forage maize	124	1100	0.027	2.97

significantly reduced by increased crop yields, as illustrated in Table 5 for a theoretical increase in yield of 20% above those shown in Table 4. The analysis requires the fertiliser N input to the crop to be increased to balance the increased N off-take (and P and K). For crops other than cereals and forage maize the effect on GHGE of a 20% increase in yield alone was greater than the combined effects of the agronomic options, ranging from a 5% reduction for main-crop potatoes to a 14% reduction in GHGE for soya beans (Table 5). This raises the exciting prospect that sizeable reductions in GHGE might be achieved by exploiting simultaneously both agronomic and plant breeding strategies, without at the same time suffering a reduction in crop output.

The scope for reducing GHGE per unit of product is markedly less for the grain legumes than for other crops. In part this is simply a reflection of the fact that these crops do not receive fertiliser N. However, it is also a reflection of relatively low crop yield - as is also the case for oilseed rape. On a protein versus energy yield basis compared to wheat, the protein-equivalent yield of beans should be 4.8 t ha^{-1} compared to the typical yield of 3.4 t/ha^{-1} (Table 4), so there would appear to be some scope for research to increase yields of grain legumes in the UK, including research into the genetic improvement of soya bean cultivars for use in the northern European climate.

The main GHGE from crop production is nitrous oxide, which accounts for about 50% of total UK agricultural GHGE on a CO_2 equivalence basis (MacCarthy et al., 2011). Of the total N_2O emissions from agriculture, about 90% is from the need to boost the fertility of soils – in any form (MacCarthy et al., 2011). Thus important areas for innovation and improvement are to increase the efficiency of use of both organic and inorganic N, to reduce the need by plants for N for growth in excess of off-take, and hence to increase NUE at constant or reduced N input. NUE is defined as off-take of N in the harvested crop as a percentage of total N input, excluding atmospheric N deposition. Estimates of NUE are in Table 7 for the typical cropping systems and also for the agronomic options to reduce GHGE described above, assuming that crop yield and composition could be maintained at typical levels *via* improved plant genetics and/or disease control at 85% of current total N input.

Typical values for NUE were in excess of 67% for all crops except oilseed rape. The agronomic options to reduce GHGE also gave increases in NUE, reflecting the fact that reductions in total N input by 20% of average levels did not produce decreases *pro-rata* in output of N in crop product (Rothamsted Research, 2006). NUE ranged from 48% for typical oilseed rape production to 97% for the 'best' system of sugar beet production (Table 7). The estimate of NUE for the best sugar beet system may be an overestimate because the nitrogen offtake estimated at the lower fertiliser N input may not have properly reflected the reduction of crop N concentration. On a long term view there must always be an excess of N supply over N off-take, since plant residues and roots contain N which break down in the soil and thus emit nitrous oxide to the atmosphere and nitrate to watercourses (Dobbie and Smith, 2003). There is also a demand for increased soil organic matter in order to store carbon in soil.

Livestock

There is a wide range between the different livestock sectors in the typical period of time the animals are housed, in feed inputs, in output of animal products and in feed conversion ratios (Table 3). It is important to note that large differences in efficiency have also been recorded *within* systems, reflecting differences in quality of land, type of livestock and management expertise (BPEX, 2008; EBLEX, 2009, 2010; QMS, 2011ab). The

Table 7: Nitrogen use efficiency (NUE, %) for typical crop systems and for options to reduce GHGE

	Typical system	No-till + no straw incorporation + 20% reduced N
	NUE (%)	
Winter bread wheat	70	79
Winter feed wheat	67	74
Winter barley	74	80
Spring barley	81	86
Winter oilseed rape	48	55
Sugar beet	85	97
Main-crop potatoes	74	93
Second-early potatoes	72	90
Forage maize	83	92

GHGE from livestock systems are shown in Table 8 in terms of kg CO_2e per kg product, per unit of edible energy and per unit of edible protein, assuming zero edible energy and protein in bone and egg shell.

Milk production has substantially lower GHGE per kg product fresh weight than the other livestock systems, but this is due to the fact that milk is largely water. On a dry matter basis GHGE from milk production is similar to that of poultry production, reflecting the energetic efficiency of converting feed into milk rather than live weight and the different chemistry of milk compared with poultry carcasses or eggs. GHGE per kg product are higher for suckled beef and sheep meat production than for beef produced from calves born in the dairy herd (dairy beef) and non-ruminant systems, reflecting the relatively high feed input to the breeding female (Table 3). Differences in GHGE between the meat production systems per unit of edible energy and edible protein are similar to those per kg fresh product, with suckler beef having the highest, and poultry meat the lowest GHGE per MJ of edible energy and per kg edible protein.

Three main technologies were found to reduce GHGE per unit of product: (i) Increased lifetime output of breeding females (fertility, fecundity and longevity); (ii) increased milk yield per year (dairy cows); and (iii) improved feed conversion ratio (growing animals). By increasing fertility (number of successful conceptions per female inseminated), fecundity (number of offspring per breeding female in sheep) and longevity (number of years in production), the annual number of herd and flock replacements were reduced. Genetic improvement of livestock was estimated to have resulted in reductions in GHGE per unit of product of about 1% per annum (Genesis-Faraday, 2008). Re-orientating livestock breeding programmes to include GHGE as selection traits was an appropriate strategy to achieve a sustained reduction in livestock GHGE. Increased fertility and resistance to disease were crucial factors in achieving increased longevity in breeding livestock. Increased fertility was achieved by feeding cows on a higher starch diet to stimulate the resumption of oestrous in early lactation, followed by a higher oil diet to encourage high conception rates (Garnsworthy, et al., 2009).

Increasing milk yield per year spreads the inputs to maintain the dairy cow over a greater output. This is not the same as breeding larger cows which have greater GHGE than smaller cows. Thus a 10% larger cow giving 10% more milk per lactation will have the same GHGE per kg milk. Increased annual milk output should also not be confused with yield per lactation, which can be increased by having a longer calving interval. Milk yield per cow life (longevity) is an important performance indicator because it affects the proportion of the total breeding herd replaced annually by first-calving heifers, and hence the total number of heifer calves reared (Garnsworthy, 2004).

A highly effective practical measure to reduce methane production by cattle is to increase the proportion of maize silage at the expense of grass silage (Tamminga et al., 2007, Weiske and Michel, 2007). Forage maize has a relatively low GHGE per kg of ME and CP of the arable crops analysed in this study (Table 6). However, the GHGE mitigation effect of forage maize may be offset by increased losses of soil

Table 8: Estimated GHGE for typical and alternative livestock systems

Sector	Typical system			Alternative system	GHGE from alternative system	Reduction in GHGE from alternative system
	kg CO_2e Per kg product	kg CO_2e Per MJ edible energy	kg CO_2e Per kg edible protein		kg CO_2e/kg product	%
Milk	1.0	0.4	30.6	Autumn-calving cows, housed 190 days/year. 8000 litres milk per year, 7 lactations per cow. 15% crude protein housed diet based on maize silage.	0.89	12
Dairy beef	8.5	1.0	49.5	Lower forage diet, housed throughout lifetime.	7.95	7
Suckler beef	15.9	1.9	90.0	Spring calving. High genetic merit cow for fertility and calf growth.	14.1	12
Sheep meat	14.6	1.6	69.3	Ewes of high genetic merit for fecundity and longevity. Low stocking rate. No housing.	11.5	21
Pig meat	4.0	0.7	19.7	High genetic merit for fertility and piglet growth. Sows and weaners outdoors. Finishing indoors on a slurry system, stored slurry immediately incorporated into land.	3.49	14
Poultry meat	2.7	0.3	14.2	Housed. Immediate incorporation of manure into land. FCR as for top 10% of sector.	2.54	7
Eggs	3.0	0.5	23.2	Housed, slurry, under-floor drying of manure, covering of manure store, immediate incorporation of manure into land. FCR as for top 10% of sector.	2.57	13

carbon if grassland is ploughed and substituted by maize crops (Vellinga and Hoving, 2011) – a factor which was not taken into account in this analysis.

There is a need to identify ways of reducing methane production in extensively grazed ruminants – possibly through plant breeding to incorporate natural methanogen inhibitory products in new herbage cultivars, or via the provision of dietary supplements which contain compounds to modify forage digestion. Higher sugar grasses may increase the capture of feed energy and protein by the rumen, improve the conversion of feed into useful animal product, and reduce methane and nitrogen emissions per unit of product (IBERS, 2011). Long chain fatty acids have also been shown to reduce methane production per unit of product in ruminants (Blaxter & Czerkawski, 1966). The mechanisms of these effects require clarification and confirmation on a larger scale.

Improving feed conversion ratio (FCR) – defined as kg feed (at constant dry matter) per kg weight gain, milk or eggs (at constant dry matter) – makes more efficient use of feed resources. Increased daily live weight gain can save resources in meat animals by reducing the total period of time needed to reach an acceptable weight and carcase composition at slaughter. However an animal that is simply larger may achieve a greater daily live weight gain but consume *pro-rata* more feed; and in this case there is no improvement in its feed conversion ratio. The analysis presented here does not distinguish between methods to improve FCR, which may be genetic, managerial, or nutritional. In some cases, diet formulations may need to be changed to achieve improved FCR. This could increase the environmental burdens of feed production and so reduce the GHGE benefit somewhat. Other improvements in animal performance, such as reducing lameness and endemic diseases, also result in better animal welfare.

The best alternative livestock systems are described in Table 8 together with the estimated percentage reduction in GHGE compared to the average for the sector (Table 8). The potential reductions in GHGE range from 7% for dairy beef and poultry meat to 21% for sheep meat. The major factors affecting GHGE per unit of milk are annual yield per cow, longevity and reduced protein diets. The alternative milk production system to reduce GHGE is therefore based on autumn-calving, cows yielding 8000 litres milk per year and given a reduced-protein diet (15% crude protein) during the housed period based on maize silage. Longevity is assumed to be 7 lactations per cow rather the current average of 3.2 lactations per cow, given that infertility is a major source of involuntary culling in the dairy herd, and that the best nutritional strategy is adopted for high fertility (60%, Garnsworthy et al., 2009). The GHGE from the alternative milk production system are 12% lower than the typical system (Table 9).

The alternative system to reduce GHGE in beef production from the dairy herd is one based on male dairy x dairy calves and beef x dairy calves in a housed system. The animals are fed on a high-energy reduced forage diet. The use of sexed semen in dairy herds was examined as a possible option. There was little effect on the total number of male and female dairy-bred calves available for beef, but its use increased calf beefing quality because a higher proportion of cows in the dairy herd were available for insemination with beef-breed semen. Sexed semen was not included in the best alternative dairy beef system. The reduction in GHGE for the best alternative system compared to the average for the dairy beef sector is 7%.

The scope for reducing GHGE from suckler beef systems is limited by the relatively high GHGE associated with the breeding cow and the relatively low output of beef per breeding female per year. Overall feed conversion ratio is substantially poorer than that of the monogastric livestock systems (Table 3). The alternative suckler system comprises spring-calving suckler cows with extended grazing (i.e. minimal housing) to minimise N_2O emissions from farmyard manure. The weaned calves are reared indoors and then finished at pasture. The GHGE from the alternative system is 12% lower than the average for the sector.

Inputs to the sheep sector are relatively low compared to other livestock sectors and the typical upland and lowland systems currently in operation in the UK are based on grazing (Table 3). The alternative sheep system is extensive, with outdoor lambing in late spring, using crossbred ewes of high fecundity and longevity. Ewes are not housed in winter. Stocking rate is relatively low −10 ewes and lambs per hectare. The reduction in GHGE of 21% compared to the average for the sector mainly reflects higher fecundity of 2 lambs per ewe compared to 1.4 lambs per ewe for the typical system, illustrating the same effect as for crops of higher 'yields'.

The best alternative pig production system comprised sows of high genetic merit for fertility and piglet growth. Sows and weaners are kept outdoors with an indoor finishing system with manure as slurry. Greater emissions of N_2O from the outdoor system are more than offset by the reduction in methane which would otherwise be produced from stored manure or slurry, giving a net reduction in global warming potential from the outdoor system compared to indoor housing of sows and weaners. There is, however, an increased risk of nitrate leaching from the outdoor system compared to fully-housed systems. GHGE from the alternative system are 14% lower than the average for the pig sector.

Poultry production is relatively efficient compared to other livestock sectors (Tables 3 and 8), and there was relatively little scope for reductions in GHGE compared to other sectors in this livestock sector, in agreement with more detailed studies of poultry meat and egg production systems (Wiedemann and McGahan, 2011; Leinonen et al., 2012a,b). The alternative system of poultry meat production is indoor-housed with immediate incorporation of manure into soil, which reduced GHGE by 4% compared to the average for the sector due to a potential saving in fertiliser for feed production. An additional 3% reduction was achieved through an improvement in FCR so that it was equivalent to that achieved by the top 10% of units, without feeding higher than average levels of dietary crude protein. The best alternative system of egg production is also indoors, with manure as slurry dried under-floor and incorporated immediately after being spread on land. This system was reflected in a reduction in GHGE of 10% compared with the average for the sector. An additional 3% reduction was achieved if the average

Table 9: Nitrogen use efficiency (NUE): Typical and alternative livestock systems

Sector	Typical system	Alternative system
	NUE (%)	
Milk	18.3	25.5
Dairy beef	16.9	18.8
Suckler beef	7.5	7.8
Sheep meat	5.8	6.8
Pig meat	26.8	28.3
Poultry meat	32.7	37.4
Eggs	24.5	28.3

FCR was improved to that currently achieved by the top 10% of units.

A continuing challenge in livestock nutrition is to define the requirement of the animal more accurately with respect to essential amino acids in order to meet requirements without over-supplying N in the diet, and to reduce excreted N, particularly as urea in urine (Weiske and Michel, 2007). Estimates of livestock NUE, defined here as N in animal product as a percentage of total N intake, for the typical and alternative systems are shown in Table 9. Values for the NUE of livestock systems were substantially lower than those for crops (Table 7). However, in calculating NUE no credit is given to nitrogen in manure, most of which is recycled into the production of crops for animal feed either directly or indirectly and which could result in longer term efficiency values considerably higher than those quoted in Table 9. Comparing different livestock sectors, the ranking of NUE is in broad agreement with that for GHGE, i.e. poultry meat has the highest and sheep meat production the lowest NUE.

There is clearly potential for improvement in livestock NUE, though it is evident from the NUE values for the alternative systems that the scope for improvement is relatively low for suckler beef, sheep meat and pig meat production. Possibly some of the alternative technologies chosen by the model for their potential effects on reducing GHGE are incompatible with others which might be selected for increasing NUE since they have relatively more impact on methane than on nitrous oxide emissions. Research is needed to confirm the extent to which diets lower in crude protein are effective in increasing NUE and in reducing GHGE in all livestock sectors without compromising animal performance. Thus at pasture the grazing animal is offered high-protein herbage which is associated with low NUE (Beever et al., 1978; Dewhurst, 2006) and novel approaches are needed to increase capture of N by the grazing animal. One reason for the apparent over-use of protein in diets for livestock is that reductions in animal performance are often seen when livestock are given diets of reduced crude protein concentrations. There is an inverse relationship between crude protein concentration of the diet and feed conversion ratio, even when (in the case of chickens) diets are given which provide essential amino acids in excess of the requirement of the bird (Ferguson et al., 1998). Thus it is often the case that animals are given diets which contain more protein than is optimal in order to maximise daily growth and minimise days to slaughter.

4. Conclusions

The main conclusion from this study was that reductions in GHGE per unit of product and increases in NUE were theoretically possible with the same technological strategies. Thus options which reduced GHGE per kg product also increased NUE, in some cases (e.g. sugar beet) apparently to values close to 100%. Differences between crops in GHGE reflected differences in yield per hectare. Thus sugar beet and forage maize had the lowest GHGE per tonne of crop and per MJ of energy because of their relatively high yields per hectare. Of the options found to reduce crop GHGE, reduced fertiliser N and increased yield per hectare were the most significant, giving reductions in GHGE of between 5% and 15% compared to typical systems.

Livestock GHGE per unit of product were an order of magnitude higher than those from crops. Values for NUE were substantially lower for livestock than for cropping systems. These results pose major challenges to those involved in livestock research, development and production in the light of likely increased future demand for milk and meat (Godfray et al., 2010).

Options found to reduce GHGE in livestock production were increased fertility, fecundity and longevity of breeding females, increased annual milk yield per dairy cow, improved FCR in meat animals and immediate incorporation of slurry following its application to land. Alternative systems were associated with reductions in GHGE of between 7% (poultry meat) and 21% (sheep) compared to the average for the sector. Small increases in NUE were also seen in the alternative systems compared to the average for the sector.

Uncertainties in the estimation of agricultural GHGE (IPCC, 2006) may make it difficult, if not impossible, to measure emissions directly on farms. Indirect indicators of GHGE, such as the technologies described in this paper, may have to be used as an alternative approach to the estimation of GHGE mitigations (DEFRA, 2011).

The results of this theoretical study show that improvements in productivity and efficiency of resource use are likely to result in lower GHGE per unit of product and increases in NUE. However the best that is likely to be achieved overall is around a 10% improvement, in agreement with the aspiration of the UK Greenhouse Gas Action Plan (Agricultural Climate Change Task Force, 2010). There is scope to reduce GHGE in all sectors by applying existing knowledge. Given the importance of nitrous oxide as an agricultural greenhouse gas, a major environmental challenge for future agricultural research is to increase NUE without compromising output or methane emissions.

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