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Can UK livestock production be configured to maintain production while meeting targets to reduce emissions of greenhouse gases and ammonia?

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ABSTRACT

We used a Life Cycle Assessment approach to determine whether the inherent differences in emissions to air among existing livestock production systems could be used to reconfigure the UK livestock sector in order to meet current greenhouse gas (GHG) and ammonia (NH_3) targets while maintaining production at current levels. Output, defined as financial value, was optimized across all sub-sectors. Using current management systems the greatest livestock output that could be maintained, while meeting emission reduction targets, was 84% of current. Adopting the most appropriate manure management practices and improved feed conversion ratio enables a further increase in outputs to 86% of current. Dairy production could be maintained at 84.1% of current if all production arises from high-yielding herds with autumn calving, all dairy cow manure is managed as slurry and diets to reduce rumen fermentation are adopted. Increasing the proportion of calves obtained from the dairy herd by 10% could maintain beef production at 85% of current. Raising finishing pigs on slurry systems, raising sows and weaners outdoors, finishing pigs at either 89 or 99 kg and improving dietary nitrogen use efficiency could maintain pig production at 87.5% of current. Manure drying within poultry buildings, immediate incorporation of poultry manures to tillage land and reduced protein feeds would allow 82.2% of current poultry meat production. Eliminating free-range egg systems and drying manure within the building could maintain egg production at 85.5% of current. Replacing lowland sheep herds (other than organic) with upland production could maintain sheep output at 86.4% of current.

1. Introduction

The 2008 Climate Change Act requires the UK to reduce greenhouse gas (GHG) emissions by 80% from 1990 levels by 2050. The agriculture sector will need to reduce annual emissions in England by 3 Mt of carbon dioxide equivalents (CO_2e) by the third carbon budget period (2018–2022) under the Government's 2009 Low Carbon Transition Plan. The EU Directive setting National Emissions Ceilings (Directive 2001/81/EC, NECD) set the UK national ammonia (NH_3) emission target as 297 t x 10^3 per year by 2010 (compared with 360 t $\times$ 10^3 in 1990). Agriculture accounts for *c.* 80% of the UK's national emissions of NH_3, with 86% of the agricultural total coming from livestock production (Choudrie et al., 2008).

Practical and effective techniques to reduce GHG emissions from UK agriculture and their cost-effectiveness were summarised by Anon. (2007a), while Webb et al. (2005, 2006) summarised UK approaches to reduce emissions of NH_3. Although the potential for increased costs and/or reduced production has been recognised in earlier work, the impacts on total national production from adopting abatement techniques have not been fully evaluated for the UK livestock industry. Moreover, the adoption of specific abatement techniques is not the only option for reducing emissions. Among existing production systems there are inherent differences in emissions, e.g. between:

- Manure managed as liquid slurry or litter-based farmyard manure (FYM).

Abbreviations: CO_2e, CO_2-equivalent; CP, crude protein; EAA, essential amino acids; EF, emission factor; FCR, feed conversion ratio; FYM, farmyard manure; GHG, greenhouse gas; GWP, global warming potential; IPCC, Intergovernmental Panel on Climate Change; LP, linear programming model; NAEI, National Atmospheric Emissions Inventory; NH_3, ammonia; NUE, N use efficiency; TAN, total ammoniacal-N.

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- Pigs raised outdoors or within buildings.
- Upland and lowland beef and sheep.

Since these systems are currently in commercial use, identifying and adopting those that produce the least emissions might be an effective means of reducing emissions while maintaining production.

In this study, we quantified systematic differences in gaseous emissions among production systems in use at the time of the study in order to assess the extent to which UK livestock production could be maintained, while reducing GHG and NH_3 emissions to meet emission reduction targets, by switching to those existing production methods that emit less GHG or NH_3. We then assessed the impact of adopting cost-effective abatement techniques on production.

The output from this exercise is an estimate of the greatest productivity, in terms of physical output and financial value of production, for each livestock sub-sector (Dairy, Beef, Pigmeat, Poultry meat, Eggs and Sheep) that can be achieved for the UK livestock sector as a whole, whilst reducing GHG and NH_3 emissions from the livestock sector. We also maximised outputs as the production of livestock protein and the total energy content of livestock produce. Since UK targets are applied at the agricultural sector level we considered an emission limit for the whole livestock industry and optimized sub-sectors accordingly and report the production implications for each individual livestock sub-sector.

2. Materials and methods

In order to evaluate fully the total GHG and NH_3 emissions arising from different modes of livestock production, including those arising beyond the farm boundary, we estimated those emissions using the Cranfield systems Life Cycle Assessment (LCA) models (Williams et al., 2006). These emission estimates will include some emissions arising both beyond the farm boundaries (hence not in the UK agricultural GHG or NH_3 inventories) and outside the UK, e.g. imported feeds and manufactured inputs. The analysis may superficially overestimate the reduction potential in the narrow sense of direct livestock emissions, but it avoids any illusions created by reducing UK emissions at the greater expense of increasing those overseas, e.g. if switching from extensive lamb to soy-based broiler meat. After all, the effects of GHG emissions are global. Ammonia emissions are much greater from livestock production facilities themselves than from feed crops, hence the changes proposed in the UK will be overwhelmingly quantified in the UK agricultural NH_3 inventory. We thus considered an LCA approach was the most appropriate methodology to enable a complete assessment to be made of emissions arising from different modes of production, e.g. upland and lowland beef and sheep.

The Cranfield systems LCA models (Williams et al., 2006) analyse individual production systems and evaluate national livestock production as the sum of the existing proportions of each production system. A production system is a combination of rearing methods, input timings, housing and manure handling systems, etc. Such discrete production systems include autumn-calving beef suckler herds; high-yielding, maize-fed dairy cows on slurry; spring or autumn calving; organic all-year calving; dairy-beef cross finishing on straw, a Most production systems require an amount of input from other production systems in the chain of production – for example dairy-beef cross finishing requires calves from dairy cattle.

The emissions and resource uses of the alternative livestock systems were analysed by constructing a system of constrained linear equations. We then explored feasible solutions to these equations (sizes of different combinations of livestock systems) to provide the optimal productivity, in terms of financial value, whilst meeting the emissions reduction targets and making use of the UK's resources. The outputs describe possible combinations of existing livestock systems that can lead to levels of financial value similar to those currently achieved by the livestock industry but producing fewer gaseous emissions than at present.

The first model section was to maximise the production of livestock products as the farm-gate price of the products. Though other metrics such as protein could be used, each sector produces a variety of other nutrients with different qualities. Price was used to encapsulate all these properties. Part of the farm-gate price includes consumer preference (e.g. organic) and in part the impact of shortage or abundance (autumn/spring), rather than simply the amount of production.

The second section expressed the logical constraints among the systems. Thus the need to produce replacements (day old broiler chicks of point of lay pullets in the case of poultry) and the different amounts of milk produced. For pigs, beef and sheep, this includes the movement of livestock from systems which raise young to other systems which produce the final commodity.

The third section was the use of resources, notably arable, grassland, hill-land. These can be limited, for example a maximum amount of hill land, or unlimited.

The fourth section set the emission constraints. 'Current' emissions were calculated using the matrix so that runs are self-consistent, by setting production to be the current, and the proportions of each system to be their current proportions. The limit is then set to 10% or 20% of these values and the resulting configurations observed.

The final section defined the current structure of the industry. For example, the proportion of cattle or pigs housed on liquid or solid manure management systems, the proportion of high-medium-low yielding dairy cows, indoor or outdoor raised pigs, housed, free range or organic laying hens.

2.1. Calculation of emissions data, productivity and resource use

Within each component livestock sub-system, the LCA model calculates the component's input requirements, outputs and emissions. For each commodity input, for example grass, the model calculates the inputs of fertilizer and machinery and emissions, and in turn calculates the inputs to fertilizer and machinery production. Emissions are calculated for the different production systems arising from management factors such as whether: livestock are raised within buildings or outdoors; excreta are managed as liquid (slurry) or FYM; livestock are raised on different planes of nutrition giving rise to different amounts of N excretion; livestock graze manufactured-N fertilized or clover-rich pasture.

To ensure that our calculations of GHG and NH_3 emissions were consistent with emissions reported by the UK's National Atmospheric Emissions Inventory (NAEI), the Cranfield LCA model was revised to incorporate activity data and EFs used in the NAEI.

When this work began (May 2007), UK emissions of GHG from agriculture were already 17% less than the 1990 baseline, while total UK ammonia (NH_3) emissions were expected to be less than the limit required by the NECD by 2010 due to the steady decrease in emissions from agriculture (262.7 kt in 2006). We therefore took the approach of estimating the impacts of further reducing emissions of GHG and NH_3 by 20% of the amounts estimated for 2006. The target of 20% was chosen to represent a significant, but potentially achievable target, which combined two real constraints on agriculture, especially the livestock sector. The initial scenario was that a reduction in GHG and NH_3 emissions could be achieved by reducing total livestock production by 20%. We then used the model, to identify modes of production, both among and within sub-sectors, with the greatest GHG and NH_3 production per t of product, The model eliminates these and increases production from other systems so that reductions in emissions of GHG and NH_3 would be at least 20% but total production is maintained as close as possible to 100% of the average for the years 2006–2008 (the baseline).

2.2. Characterising livestock outputs

We used data from the Food Standards Agency (FSA) (2002) and United States Department of Agriculture (USDA) (2009) to estimate protein in each product and made estimates of the kill-out percentage during processing using information derived from Jones et al. (2009) (Table 1). Meat contains other nutrients (e.g. vitamins and minerals), not covered by these two attributes, which are better represented by a financial value measure for which the best (perhaps only) estimate is the selling price of a carcass. This may be regarded as an integration of the different components of value. Table 2 shows the protein and energy content per £ value of each livestock product. Beef and sheep provide the least protein, and a high price for their protein content, perhaps reflecting their other perceived benefits (e.g. sensory) by the consumer. Milk contains protein, fat and lactose in roughly equal amounts, so protein poorly represents its nutritional value compared with meat. Milk in the LCA model is taken to contain 4% fat, 3.3% protein and 4.5% lactose. In the LCA model eggs weigh 60 g and contain vitamins, minerals, 12.5% protein and 11.2% fat, but only traces of carbohydrate (Williams et al., 2006).

2.3. Linear programming

The problem of finding the proportions of each system which meet the emission targets is a series of constrained linear equations. The 'what configurations' question can be expressed in a mathematically simple way as – find the values of x_{ij} such that:

$$\text{Maximise} \sum v_{ij}x_{ij}, \text{ such that } \sum g_{ij}x_{ij} \le G \text{ and } \sum a_{ij}x_{ij} \le A$$

where i is the commodity, j the subsystem and v, g, a are the output, global warming potential (GWP) and NH_3 emissions respectively, of each subsystem. This is a linear program (LP) that determines the combination of systems, which maximises output whilst achieving the objectives of reduced emissions. Further constraints need to be added to this simple LP in order to describe properly the interactions between systems of production and land use. The matrices for each sub-sector were combined into a single matrix for the whole livestock industry which is available as supplementary data (Table S1). The solution of the model is the combination of production systems that achieve the maximum productivity while reducing GHG and NH_3 emissions by 20%. Entering data for alternative structures and systems enable different levels of production to be achieved.

Table 2
Energy and protein purchased for each £ value of the product.

Per pence	Sheep	Pigs	Beef	Chicken	Eggs	Milk
Protein (g)	5.6	14.6	6.9	17.2	15.4	15.3
Energy (kJ)	257.5	532.2	324.7	653.6	774.1	1274.4

Protein in each type of meat and milk from the Food Standards Agency (FSA, 2002) and USDA (2009).
Loss of weight during processing from Jones et al. (2009).

Structure constraints impose such things as the proportion using slurry, outdoor rearing or level of feeding. The possible configurations using the best available production systems can be ascertained by removing structure constraints. Any intermediate configuration can be derived from these results. For example, in a system in which 60% of manure is currently handled as slurry (with 40% as FYM), the 80% emission limit will give 80% production. If the best system is found to be no slurry (i.e. 100% FYM), and this gives 86% of production, simple interpolation applies so that with 30% slurry (half the change), 83% production will be possible. In this case, 1% more production is possible for every 10% less slurry. Thus, in each case we determined the extreme value of the best configuration that can be achieved, so that any solution between the cases could be derived. In addition to exploring feasible combinations of livestock systems that provide the greatest productivity whilst meeting the reduction targets, the model was also parameterized with proven and practical GHG and NH_3 abatement techniques (see Section 2.4. below) to assess their impact on production as well as emissions.

2.4. Abatement options

Abatement and improvement options were analysed by deriving new values for the coefficients for each production system in the matrix. The abatement options incorporated into the model are available as Supplementary Material (Table S2).

Potential measures to reduce emissions of GHG may be summarized as: reduce protein intake to better match animal requirements; increase the proportion of maize or high-sugar grass in ruminant diets; rumen manipulation by adding ionophores to ruminant diets; genetic modification of rumen microflora; use of nitrification inhibitor with N fertilizers; anaerobic digestion; improving animal health to promote efficiency; breeding to promote better lifetime feed conversion efficiency (Anon., 2007b).

Table 1
Estimates of the protein, fat, carbohydrate and energy contents of livestock products from two data sources. All as g per 100 g apart from energy (kJ per 100 g).

Source		Whole fresh milk	Poultry meat	Pig meat	Beef	Eggs	Sheep meat	Turkey meat
FSA (2002)	Water	87.6	40.0	37.5	34.0	75.1	33.5	42.0
	Protein	3.3	14.7	16.4	15.4	12.5	14.9	18.0
	Total N	0.5	2.4	2.6	2.5	2.0	2.4	2.8
	Fat	3.9	8.4	8.6	6.7	11.2	11.5	6.2
	Carbohydrate	4.5	0.0	0.0	0.0	0.0	0.0	0.0
	Energy	274.0	560.0	596.0	512.0	627.0	680.0	535.0
USDA (2009)	Water		40.0	37.5	34.0	NA	33.5	42.0
	Protein		11.1	10.5	10.3	NA	9.3	12.1
	Total N		NA	NA	NA	NA	NA	NA
	Fat		8.9	26.4	14.3	NA	11.9	4.6
	Carbohydrate		NA	NA	NA	NA	NA	NA
	Energy		724	1186	538	NA	617	391

Notes NA = Not available.

Only the first two of the GHG measures were quantified. Rumen manipulation has yet to be proven on commercial farms and some of the methods proposed are not currently allowed under EU regulations. There are few clearly demonstrated synergies among measures to reduce emissions of GHG and NH_3, the main one is that measures to reduce excess protein in diets and to improve carbohydrate digestibility have the potential to reduce emissions of N_2O, CH_4 and NH_3.

Proven methods to reduce NH_3 emissions from agriculture (Webb et al., 2005, 2006; Nwedega et al., 2008) may be summarised as: reduced-protein diets (while supplying sufficient essential amino acids (EAA) and total protein for the animal's needs); minimise emitting surface area within buildings; remove manure frequently from buildings; filter exhaust air from buildings; cover manure stores; inject or incorporate manure into soil soon after application; apply slurry by methods which reduce exposure to air (e.g. trailing hoses or shoes).

2.5. Uncertainty

All scientific measurements and models are uncertain. The way in which uncertainties are aggregated in LCA tends to reduce the errors, but how these should be treated in a comparison is still debatable. This was not an experiment in which two normal distributions may be compared using a statistical test. In other similar system models, the uncertainty (quantified as the coefficient of variance) may be *c.* 25%–35% for NH_3 emissions, but possibly over 50% for N_2O. As it is a model, in many cases the uncertain coefficient is the same in both cases and therefore its resulting uncertainty of the difference is zero. For example in comparing different fecundity of sheep, the uncertainty due to the N_2O emissions from grass are zero. The text that follows should, however, be read with qualification that calculated statistical significance is not implied in any statement.

3. Results and discussion

The results give the level of production that can be achieved whilst reducing GHG and NH_3 emissions from UK livestock production by 20%. If no changes are made to the proportions of baseline production systems then clearly emissions of GHG and NH_3 can only be reduced by 20% by reducing livestock numbers by 20%: all emissions will be reduced *pro rata* from all sub-sectors. We first consider the greatest livestock production that can be maintained while reducing GHG and NH_3 emissions by 20%. We then report how production may be optimized within each individual sub-sector. Throughout when we refer to 'optimization', the 'optimum' or 'baseline' we are referring to the financial value of production to the producers, except where we state otherwise.

3.1. Optimization among all sub-sectors

The financial value of livestock production is optimized by reducing beef production by 54% (by eliminating suckler herds) and reducing lamb and pig meat production by 11 and 6% respectively (these results not shown). This configuration is also optimal when output is expressed as the energy content of food.

However, we considered that, although it would be a true optimization of livestock production, it would be unrealistic to concentrate reductions almost entirely in one sub-sector. We therefore modelled solutions obtained from constraining production from an individual sub-sector at a minimum of at least 72% of baseline output, firstly in the sub-sector (beef) which had been reduced to 54%. This was progressively repeated, with each sub-sector in turn fixed at 72% of output (Table 3).

Maintaining beef production at 72% of baseline, using existing management systems, allowed total livestock output to be 84% of baseline (Table 3). The optimum was now achieved by reducing lamb production by 60% and pigs by 44%. The addition of abatement techniques allowed production of milk, pigs, poultry meat and eggs to be maintained at 100% and total livestock production to be maintained at 86% of the baseline. However, output from the sheep sub-sector was now reduced to just 15% of the baseline.

Constraining output from the sheep sub-sector to be 72% of baseline, using existing management systems, allowed a total output value of 83% of baseline. Pig production was now reduced by 33% and dairy production by 14%. The adoption of abatement

Table 3
Optimization of overall production while maintaining at least 72% of financial output. Solutions derived from re-configuring production across sectors using either current management practices alone (CMP) or in combination with abatement techniques (CMP + AT).

a) Value	Maintain 72% beef		Maintain 72% sheep		Maintain 72% pigs		Hill	
	CMP	CMP + AT	CMP	CMP + AT	CMP	CMP + AT	CMP	CMP + AT
Total Value, £m	6487	6650	6380	6458	6366	6481	6263	6336
% of base value	*84*	*86*	*83*	*84*	*83*	*84*	*81*	*82*
Production								
Lamb carcass, kt	109	41	195	195	195	195	288	287
Pig carcass, kt	387	692	461	692	498	1245	541	692
Beef carcass, kt	516	516	516	516	516	516	516	516
Poultry carcass, kt	1468	1468	1468	1468	1468	1468	1468	1468
Total carcass t, kt	*2480*	*2727*	*2640*	*2871*	*2677*	*3424*	*2813*	*2963*
Eggs, million	8872	8872	8872	8872	7686	8872	8872	8872
Milk, M litres	13,619	13,619	11,673	10,832	11,682	8059	9570	9144
Land Use, M ha:								
Arable	2.43	2.63	2.40	2.53	2.40	2.78	2.38	2.46
Grassland	2.33	2.10	2.57	2.55	2.57	2.49	2.83	2.82
Hill	1.22	0.62	2.03	2.06	2.03	2.16	2.91	2.91
Emissions								
N_2O–N, 10^3 t	21.5	21.2	21.8	21.7	21.8	21.9	22.2	22.1
CH_4, 10^3 t	518	513	513	508	514	488	507	504
CO_2, 10^3 t	6259	6590	6186	6367	6184	6772	6108	6229
GWP_{100}, Mt CO_2e.	30.130	30.130	30.130	30.130	30.130	30.130	30.130	30.130
% of base GWP	*80*	*80*	*80*	*80*	*80*	*80*	*80*	*80*
Ammonia, 10^3 t NH_3–N	152	152	152	152	152	152	152	152
% of base NH_3–N	*80*	*80*	*80*	*80*	*80*	*80*	*80*	*80*

Key GWP_{100}, global warming potential over 100 years.

techniques maintained total output value at 84% of baseline, with milk production reduced by 20% and the pig, poultry meat and egg sub-sectors at 100% of baseline.

Constraining pig production to be 72% of baseline with existing systems achieved total output value of 83% of baseline. Egg and dairy production needed to decrease by 13 and 14% respectively. Total output was maintained at 84% of baseline by the adoption of best manure management systems.

3.1.1. Making more use of hill land

The above results leave 1 Mha of the 2.91 Mha of hill land unused. Ecosystem service provision would be reduced if large amounts of hill land were not used for agriculture so we determined the configuration of livestock which uses this land and reduces GHG emissions by 20%. The solution only allowed production at 81% of baseline. Pig, beef and dairy production would be reduced by 22, 28 and 30% respectively while lamb production increased by 6%. The adoption of abatement techniques enabled pig production to be maintained at 100% of baseline but milk production decreased by 33% giving total output of 82% of baseline.

3.2. Optimization of individual sub-sectors

3.2.1. Dairy

Dairy production may be maintained at 83.6% of baseline, without the introduction of abatement measures, if all production arises from autumn-calving high-yielding herds and all dairy cow manure is managed as slurry (while that from replacement animals is managed as FYM) (Supplementary Material, Table S3), although the seasonality of milk supply would change somewhat. Immediate incorporation of manures to tillage land and injection of slurry to grassland can lead to substantial (13–31%) further reductions in emissions of NH_3. However, by increasing the amount of N entering the soil, this may lead to small increases in emissions of N_2O (Webb et al., 2010), while the additional power requirement of injection slightly increases emissions of CO_2 (<1%, Hansen et al., 2003). Hence there is no net decrease in emissions of GHG.

Reducing the crude protein (CP) content of feed has a disproportionate benefit in reducing the total ammoniacal-N (TAN) (the source of NH_3 emissions) content in excreta, since excess N is excreted in the urine (Smits et al., 1995). Losses of N_2O are proportionate to total N excreted, whereas emissions of NH_3 are related to TAN (Webb and Misselbrook, 2004 and references therein). However, reducing feed CP only allows an increase of 2.7% in milk production. This is because CH_4 emissions are increased by 2.7% which partially offsets the savings in N_2O (−2.4%) and CO_2 (−3.0%) emissions.

The greatest production level can be achieved by combining adoption of the above NH_3 abatement techniques with production only from high-yielding herds in combination with highly-digestible diets to reduce rumen fermentation. These allow 84.1% of the baseline production to be achieved.

3.2.2. Beef

Within existing management systems, the sourcing of calves from the dairy sub-sector has the potential to maintain beef production fully while enabling reductions of 20% in emissions of GHG. The option arises because a dairy cow completing *n* lactations requires only *c. 1/n* viable heifer calves to maintain the dairy herd. In practice > *1/n* are needed as some heifers are infertile. The remaining calves are surplus to requirements and may be sold to beef producers to be raised for meat. If 10% more calves reared for beef were from the dairy herd then 85.0% of baseline beef production could be obtained (Supplementary Material, Table S3a). If *all* the calves were from dairy, GHG emissions decrease to 64% of the required emissions limit and the relationship between calf sourcing and emissions is linear. However, this can only be achieved if the *number* of dairy cows is increased, and implies a different breed of dairy cow. If the average number of dairy lactations were increased to 7 (similar to that for beef cows), then a 10% increase in beef from the dairy herd can be achieved. This, of course, conflicts with the trend for greater dairy yields and the use of Holsteins.

Another option is to produce beef from hill suckler herds which emit less N_2O than other beef herds. Hill systems rely on grazing where the calf is sold for finishing in better conditions. However, to achieve 100% of baseline production within the emission limits would require more hill land (4.21 Mha) than is available (2.91 Mha). Limiting the area of hill land to 1.33 Mha allows only 81% of baseline production. The greater proportion of time spent grazing in upland systems than lowland systems leads to a potential further reduction in NH_3 emissions to 66% of baseline. This is because a much smaller proportion of TAN voided during grazing is lost as NH_3 than that voided in and around buildings (Webb and Misselbrook, 2004).

3.2.3. Pigs

Pig production may be maintained at 85.4% of baseline by raising all sows and weaners outdoors (finishing is almost entirely indoor in the UK). This reduces GHG emissions by 20% but NH_3 emissions by 36% (Supplementary Material, Table S3c). By allowing the optimum choice of finishing weight, pigs are finished at either 'light' (mean of 89 kg) or 'medium' (mean of 99 kg) weights rather than 'heavy' (mean of 109 kg) weight, due to the slightly poorer feed conversion ratio (FCR) of heavy pigs. This enables a further small increase in potential meat production by allowing more pigs to be raised in relation to GHG emissions. Land use (which is the land used to produce the feed for the pigs) is reduced pro-rata to the reduction in pig production. In all of these scenarios, the limiting factor is the need to reduce GHG emissions from pig production by 20%. In all cases, NH_3 emissions are reduced by more than 20%.

The introduction of NH_3 abatement measures enables only a marginal further maintenance of production to 86.5% of baseline. This is because although emissions of NH_3 are reduced by 50%, there is little or no effect on emissions of GHG. Improved N utilization efficiency (NUE), abatement measures, and optimising existing systems allows total production of 87.5% of baseline while reducing GHG emissions by 20% and NH_3 by 68%. The limited increase from NUE is because most of the reduction is in emissions of NH_3 with just a 3% reduction in N_2O emissions.

3.2.4. Poultry meat

Optimizing existing systems can only maintain production at 80.7% of baseline (Supplementary Material, Table S3d). This is achieved mainly by eliminating free-range production as free-range birds consume more feed than those entirely housed, although production is no greater. If the FCR is improved by 10% then, despite the saving in GHG emissions from the production of feed, poultry meat production increases by only 0.2%.

Introducing NH_3 abatement techniques *reduces* production. Drying manure consumes energy which increases GHG emissions. Immediate incorporation reduces NH_3, but not GHG emissions. There is a small saving in N fertilizer use, but the increase in production is negligible. Improving N utilisation, thereby reducing the N fertilizer applied, only increases production a little. Current information does not suggest any reduction in N_2O emissions from drying manure. However, manure drying is effective in reducing emissions of NH_3 because drying inhibits bacterial activity and stops the conversion of uric acid to urea which prevents NH_3

emission (Groot Koerkamp, 1994). If the bacterial conversion of uric acid is effectively inhibited, it seems logical to assume that nitrifying and denitrifying bacteria will also be inhibited, and emissions of N_2O will be reduced. If this is the case, and N_2O is reduced in proportion to NH_3, then a further 2.2% maintenance of production can be obtained.

3.2.5. Egg production

Restricting egg laying to housed flocks allows production of 83.5% of baseline levels within the GHG and NH_3 constraints (Supplementary Material, Table S3e). This is because free-range birds consume more feed than those entirely housed (Dekker et al., 2011; Leinonen et al., 2012b), although production is no greater. Drying the manure requires some energy which increases GHG emissions, but because the NH_3 is reduced, it was assumed the N_2O emissions are also reduced *pro-rata* as was done for poultry meat production. The net effect is to enable production to be maintained at 85.5% of baseline while emissions stay within the GHG limit. The NH_3 is again not limiting.

3.2.6. Sheep

Sheep meat production can be maintained at 86.4% of the original by restricting lowland production to solely organic, producing one third of the total, with the remainder produced non-organically in the uplands (Supplementary Material, Table S3f). The main advantage of the lowland organic system is the much longer life of the ewes (6 years) and non-organic lowland has the disadvantage of 30 days of housing (for early lambs) which gives slightly greater NH_3 emissions than systems in which the sheep are never housed. Note that the optimum GHG/NH_3 choices have consequences for seasonality of lamb production.

4. Discussion

Our results present the challenge of balancing reductions of gaseous emissions with minimizing reductions in farm production and hence income. Alternative approaches might emphasize a consumer-oriented approach of maintaining the nutritional outputs of protein by weight and energy as kJ. Such output was also generated by the model and indicated that, overall, emissions per unit of production are little altered whether optimised in terms of financial value, protein or energy: providing 86, 93 and 95% respectively of current production (Table 3). In all cases, current production of poultry, eggs and dairy products is fully maintained when beef production is fixed at 72% of baseline whether outputs are optimized by value, protein or energy outputs.

4.1. Optimizing existing systems

Our results indicate that, if the UK livestock industry were to optimize production to reduce GHG and NH_3 emissions by 20%, by far the biggest reduction in output (54%) would take place within the beef sub-sector. This is because, per t of product, GHG emissions per t of beef tend to be greater than per t of other livestock products. Yet, in the global context, GHG emissions from UK beef production are less than from some other producers (Webb et al., 2013). Hence from the perspective of global emissions it is reasonable to identify means by which UK beef production may be maintained while emissions are reduced. UK beef production could be maintained at 100% of the baseline if beef calves were sourced from the dairy industry but to do so would require major changes in UK dairy production.

The historic focus on increasing annual milk yield per cow, which Vellinga et al. (2011) considered an effective GHG mitigation option, has decreased the longevity of dairy animals and increased the proportion of replacement animals (Stott et al., 1999). The average productive lifespan of dairy cows had decreased in the past thirty years from an average of 4.8 lactations per cow to an average of 3.8 in 2006–8 (Hanks and Kossaibati, 2013), but appears to have stabilised in recent years. Cows which died in 2009 had, on average, lived for 6.8 years and produced milk for 4.3 years (Pritchard et al., 2013). This is in spite of the fact that dairy cows can expect to live 8 years (6 lactations) before their health begins to deteriorate. The first two years of a cow's life are spent growing and developing so the heifer is producing CH_4 and consuming feed without producing milk. Also, the options for increasing resource use efficiency by increasing milk production per cow are very limited for current outputs of 7500–9000 L milk per cow per year (Vellinga et al., 2011), which is the range of outputs typical of much of UK production. Hence increasing the longevity of dairy cows, by reducing the proportion of replacement animals (followers), could reduce GHG emissions providing total lifetime milk production is increased. Lovett et al. (2006) concluded that the greatest reductions in GHG emissions can be achieved by feeding medium-potential cows with the greatest levels of concentrate feeds. Flysjö et al. (2012) concluded that further increasing milk production per cow, when production is already large, does not necessarily reduce total GHG emissions when the impacts on related systems are taken into account. Vellinga et al. (2011) considered that the focus should be on realizing an increased feed efficiency, rather than on high milk production *per sé*. This creates the optimum balance between the goals of increasing milk yield, and hence reducing GHG emission per L. Increasing the cows' productive lives can improve the margins for the herd. However, reducing the replacement rate demands very good management skills.

Further intensification of dairy production runs counter to the finding that emissions from beef production can be greatly reduced, while maintaining current production, by sourcing calves from the dairy industry. This would require breeding dual-purpose cattle for the dairy herd producing less milk. On an *individual* basis there are no breeds or crossbreeds that can currently match the productivity of pure Holsteins (Hanks and Kossaibati, 2013) which, with related Frisians, comprise about 90% of UK dairy cows (Dairy Farming, 2012). However, stocking rate is likely to affect output as will diet; high-yielding animals produce large quantities of milk due in part to high-energy diets (McDonald et al., 2011). Fuller (2001) argued that when crossed with native breeds Friesians were long-lived and highly fertile and did well on low-cost feeding regimes producing well-conformed beef offspring. Crossbred cows have more than a year's advantage in longevity and 30% greater lifetime productivity compared with purebred animals (Hocking et al., 1988). The increasing use of Holsteins has reduced these advantages and contributed to the short cow lifespan of the UK herd. Heavier dairy cattle tend to have greater pressures imposed on hooves and are prone to lameness, a major contributor to dairy cow culling (Archer et al., 2010). Genetic testing products on the market claim to be able to identify cows with a longer potential longevity from which to breed, something that would previously only be accomplished by a mixture of selective breeding and trial and error. Hence there would appear to be a need for a detailed study of the potential interactions between options to improve resource use efficiency in the dairy sub-sector and how this goal could be integrated with that of producing cross-bred calves that could be used for beef production.

Technology, such as semen sexing (which may be expensive now but could become more economical), would improve the beef quality of the calves from the dairy herd and should increase the proportion of the beef from the dairy herd.

Concentrating beef production on hill land would be consistent with the strategy proposed by Garnett (2007) for marginal livestock production, i.e. raising livestock on land unsuitable for arable production and on which there may be biodiversity benefits from the maintenance of grazing.

4.2. Improved systems

Combining improved diets with spreading techniques that reduce NH_3 emissions offers the greatest potential for reducing both NH_3 and N_2O emissions from dairy farming. However, some of the more effective NH_3 reduction options either have no impact on GHG or may lead to small increases.

Emissions from the UK poultry sub-sector are forecast to increase due to increased numbers and to welfare considerations leading to more free-range production and increased floor allowance for indoor birds (Leinonen et al., 2012a, 2012b). Previously caged hens were given 550 cm^2 of space per bird but since 2012, non-enriched cages are banned and hens must have 750 cm^2 per bird. Increasing the floor area per bird is expected to increase NH_3 emissions by increasing the surface area to volume ratio of the manure voided by the birds onto the floor, unless measures are taken to keep the manure dry and remove it to storage. Current building designs can enable this as manure is collected on belts for frequent removal from the building, often after being dried on the belt. Leinonen (pers. comm.) reported that the physical performance (eggs per unit feed consumed) of hens in enriched cages was little different to battery cages so that the advantage of higher feed conversion efficiency should apply in these systems.

Incinerating broiler litter to generate electricity can reduce the net GHG emissions from poultry meat production (Leinonen, pers. comm.). Improving the thermal performance of buildings used by fully housed livestock should reduce the energy needed for heating and/or ventilation. In the UK, some broiler producers have installed combined heat and power generators using broiler litter produced on the farm while others have introduced heat exchangers to reduce energy costs. Leinonen et al. (2014) found that heat exchangers in low density broiler houses could reduce GHG emissions by 5%.

We found that for several sub-sectors (dairy, pigs and poultry) the adoption of NH_3 abatement techniques would enable maintenance of production closer to the baseline while achieving or exceeding the necessary reduction in NH_3 emissions. But it was harder to reduce GHG emissions by 20% without similar reductions in output. The reason for this difference lies in the nature of agricultural GHG emissions which are dominated by CH_4 and N_2O. In contrast to NH_3 emissions, GHG emissions are not episodic, occur throughout the year, and comprise only a small proportion of input N and C. Methods to abate NH_3 emissions are conceptually simple and lend themselves to straightforward abatement methods, such as reduced-emission manure spreading which achieve very large (often >70%) reductions in emissions. Uptake of such options may add to costs but need not reduce output. Equally effective options do not exist for N_2O and CH_4 other than to greatly reduce fertilizer-N inputs or ruminant populations either of which will greatly reduce output. Doole (2014) recently reported the difficulty of identifying cost-effective measures to reduce GHG emissions from dairy farming. In contrast, a recent study by Elliot et al. (2014) did find some cost-effective approaches by improving cattle health.

4.3. Trends in UK livestock production

In contrast to the other UK livestock sub-sectors, which are expected to remain fairly static, forecasts suggest poultry numbers are likely to increase from the 2006–8 baseline by *c.* 5% by 2020. Between 1990 and 2006 total emissions of NH_3 increased little, despite a *c.* 40% increase in numbers. This was due to the introduction of phase feeding and the use of SEAA in diets. However, although some further improvements to the N balance of poultry feeds is forecast, the potential to reduce emissions from this sub-sector by further reductions in protein concentrations in feed will decrease as there are limits to the extent to which the protein content of poultry rations can be further reduced (e.g. Namroud et al., 2008). Nevertheless, better environmental performance is becoming one of the targets of broiler breeding programmes and breeding to improve feed efficiency, was considered to have the potential to reduce the environmental impacts of broiler production by Leinonen et al. (2012a). Heat exchangers are also beneficial (Leinonen et al., 2014).

4.4. National emission targets and leakage

These results suggest that 20% reductions in emissions of GHGs and NH_3 can only be obtained by reducing UK livestock production by *c.* 14%. However, given the demand for livestock produce it is likely that any shortfall in UK production would be met by increased imports and increases in production, GHG and NH_3 emissions elsewhere. In addition, increases in production may take place using production systems with inherently greater emissions than those currently used in the UK. For example, Webb et al. (2013) found that, per t of produce, GHG emissions from beef production in Brazil were much greater than those from UK production while the GHG emissions per t arising from poultry produced in the UK was 7% greater than that of poultry raised in Brazil. This was a consequence of warmer temperatures in Brazil requiring less heating, less energy required to transport soya feed to the farms and to the great majority of electricity in Brazil being generated from renewable resources. Hence from the perspective of global GHG emissions it might be argued that it would be better if it were UK production of beef that was to increase, rather than that of poultry, whereas adjusting UK livestock production to maximise UK GHG-constrained output would lead to a reduction in beef production. These findings suggest that current national emission reduction targets should be complemented by international agreements to reduce emissions by identifying regions and modes of production with the greatest and least emissions and incentivising the transfer of production to those regions or modes of production which produce the least emissions per t of produce. This would reduce the risk of rigid adherence to national targets leading to the transfer of emissions elsewhere.

4.5. Top-down approach and the free market

We acknowledge that the approach applied here is not in accord with market principles. Large parts of sub-sectors will not abandon farming in favour of other producers for purely altruistic reasons. Our findings help to understand the constraints that exist in meeting mitigation targets. They show that a critical appraisal of the future structure of, for example, the cattle herd is vital if future emission reduction targets and production outputs are to be met.

5. Conclusions

If the UK livestock industry were forced to reduce GHG and NH_3 emissions by 20% then by optimizing production across the entire UK livestock sector total production could be maintained at 86% of the baseline value but would require a reduction in the production of beef, lamb and pig meat by 54, 11 and 6% of baseline production respectively. By limiting the reduction of the beef sub-sector to 72% of baseline overall production could be maintained at 86% of baseline and would enable 100% of current production by the dairy, pig, poultry meat and egg sub-sectors respectively but lamb production would have to decrease by 85%. Limiting the decrease in production by any sub-sector by 72% would lead to overall production being no more than 83% of the baseline.

For the dairy sector, there is scope, from a combination of optimizing current systems and the adoption of proven abatement techniques, principally reduced-emission spreading techniques and diets with less protein and roughage, to reduce gaseous emissions by 10% while maintaining production almost at current amounts. This would, however, require the conversion of 15% of the current grassland area to arable. Sourcing more beef calves from dairy herd maintains output and reduces GHG emissions, but this is contingent on the supply from the dairy herd, which depends on demand for milk.

Ammonia emissions can be reduced to the targets set without reducing production, albeit while imposing costs on the industry, but GHG emissions from livestock farming cannot be reduced by 20% without reducing output. This is because while means to abate NH_3 emissions are conceptually simple and lend themselves to straightforward abatement policies, the identification of such techniques to enable large reductions of GHG emissions has proved difficult.

These findings imply that, ultimately, the only means of substantially reducing GHG from livestock production in the UK, without simply exporting production and emissions to other countries, may be to substantially reduce consumer demand for livestock products.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.06.085.

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