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How can we improve the environmental sustainability of poultry production?

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The review presents results of recent life cycle assessment studies aiming to quantify and improve the environmental performance of UK poultry production systems, including broiler meat, egg and turkey meat production. Although poultry production has been found to be relatively environmentally friendly compared with the production of other livestock commodities, it still contributes to environmental impacts, such as global warming, eutrophication and acidification. Amongst different sub-processes, feed production and transport contributes about 70 % to the global warming potential of poultry systems, whereas manure management contributes about 40–60 % to their eutrophication potential and acidification potential, respectively. All these impacts can be reduced by improving the feed efficiency, either by changing the birds through genetic selection or by making the feed more digestible (e.g. by using additives such as enzymes). However, although genetic selection has the potential to reduce the resources needed for broiler production (including feed consumption), the changing need of certain feed ingredients, most notably protein sources as a result of changes in bird requirements may limit the benefits of this strategy. The use of alternative feed ingredients, such as locally grown protein crops and agricultural by-products, as a replacement of South American grown soya, can potentially also lead to improvements in several environmental impact categories, as long as such feeding strategies have no negative effect on bird performance. Other management options, such as improving poultry housing and new strategies for manure management have also the potential to further improve the environmental sustainability of the poultry industries in Europe.

Environmental impacts: Feed ingredients: Life cycle assessment: Poultry systems

Livestock production systems are generally considered to have various negative environmental impacts, including nutrient leaching and a significant contribution to global warming[1]. The latter has been especially considered to be a major issue, as it is difficult to handle and arises from various sources. For example, ruminant production is problematic as a result of high output of methane, a powerful greenhouse gas (GHG) from enteric fermentation. Furthermore, ruminants generally require large areas of grazing land and therefore in some parts of the world are associated with land use changes (LUC), such as deforestation, which in turn contribute to global GHG emissions.

In non-ruminant production systems, the problems mentioned earlier can be largely avoided. However, non-ruminant production has its own concerns in terms of environmental sustainability[2–4]. For example, these systems are very much dependent on external feed production, and especially they require imported protein sources, most notably soya, the production of which has been associated with various environmental impact issues. Amongst livestock systems, poultry production has been found to be relatively environmentally friendly[5–7]. Despite relatively low GHG emissions, poultry systems still have some features that require special attention in terms of their

Abbreviations: AP, acidification potential; CO_2, carbon dioxide; DDGS, dried distillers grains with solubles; EP, eutrophication potential; GHG, greenhouse gas; GWP, global warming potential; LCA, life cycle assessment; LUC, land use changes; ME, metabolisable energy; NH_3, ammonia.
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environmental impacts. These particularly include nitrogen emissions, for example in the forms of ammonia (NH_3) emissions to air, nitrous oxide emissions that contribute to global warming and nitrate leaching.

To improve the environmental sustainability of livestock systems, including poultry production, the first requirement is to have a systematic tool which can quantify holistically the level of environmental impacts arising from the production, and then identify the potential target areas for environmental improvement. In this review, we discuss the results of studies that have used a method called life cycle assessment (LCA) to quantify such impacts for poultry production, mainly in the UK; some of the issues developed here are relevant to other European poultry production systems that face similar challenges. The results: (i) show the relative environment impacts of different poultry production systems; (ii) demonstrate the contribution of different subsystems (production of feed, housing emissions, manure management, etc.) to their overall impacts; and (iii) finally suggest management measures, including nutritional ones, which could make the poultry production even more environmentally friendly.

Life cycle assessment: a tool for quantifying the environmental sustainability

In public discussions, improving environmental sustainability of agricultural production has often been considered to be related only to direct farm activities; for example the possibilities of reducing the energy use on farms, or reduction of direct emissions to environment, including NH_3 and methane emitted from animal houses or fields[8]. In reality, however, a large part of the overall environmental impacts related to livestock production actually comes from indirect sources. For example, the production of feed for animals requires growing of feed crops, which consumes energy and has emissions to environment, and then transporting them over, sometimes, very long distances, e.g. soya from South America to Europe.

It should also be noted that sometimes the direct and indirect sources of environmental impacts can have complicated interactions. In theory, it could be possible that improving one aspect of production can actually have harmful indirect environmental effects in some other part of the production chain. For example, changing the composition of the livestock feed in order to reduce nutrient emissions from manure inevitably changes the demand for various feed ingredients, and this change may either reduce or increase the environmental impacts related to feed production. Furthermore, some activities in livestock production may have both environmental benefits and burdens at the same time. For example, using livestock manure as a fertiliser may reduce the burdens of the production of manufactured fertilisers, but it may also increase nutrient leaching and emissions to the atmosphere[8].

As a result of these potentially complex interactions and trade-offs, a systematic, quantitative approach is needed to evaluate the environmental impacts in agricultural systems, including livestock production. LCA accounts for all environmental burdens occurring during the production cycle, starting from raw material extraction through to the end products[9]. The LCA studies of poultry production presented in this review are mainly based on a systems modelling approach. This includes structural models of the industry and process based simulation models that are unified in a systems approach which handles possible interactions between separate subsystems[5,10–13]. In this approach, a structural model for a poultry production system calculates all the inputs required to produce a specific functional unit (e.g. 1000 kg expected edible carcass weight of broilers or turkeys or 1000 kg eggs) and outputs coming from the system, including useful products and unwanted, necessary outcomes, e.g. wastes, mortalities and emissions to the environment. In the systems model, changes in the proportion of any activity must result in changes to the proportions of other activities in order to keep producing the desired amount of output. For example, production of a certain amount of eggs requires a certain number of laying hens, which requires a number of pullets (taking mortality into account), which in turn requires a certain number of parent birds and so on, and all these need to be quantified by the systems model.

As an output, the LCA model quantifies the emissions to the environment (per functional unit) and these can be aggregated into environmentally functional groups as shown in the following examples:

Global warming potential (GWP) is a measure of the GHG emissions to the atmosphere. The main sources of GWP in poultry production are carbon dioxide (CO_2) from fossil fuel and LUC, nitrous oxide and methane. The sum of GWP per functional unit is also known as the carbon footprint.

Eutrophication potential (EP) is used to assess the over-supply (or unnatural fertilisation) of nutrients as a result of them reaching water systems by leaching, runoff or atmospheric deposition. The main sources are nitrate and phosphate leaching to water and NH_3 emissions to air.

Acidification potential (AP) is mainly an indicator of potential reduction of soil pH. The main source is NH_3 emissions, together with sulphur dioxide from fossil fuel combustion.

Furthermore, LCA can quantify various resources associated with production of the functional unit in question. These include, for example, Primary Energy Use, which is quantified in terms of the primary energy needed for extraction and supply of energy carriers, including gas, oil, coal, nuclear and renewable. Other possible indicators of resource use are land occupation, which describes the area of the land required to produce a unit of the product (in the case of poultry production, this mainly consists of the arable land for producing crops for feed), abiotic resource use, which describes the use of non-renewable raw materials, such as fossil fuels and minerals, and water use.

Environmental hotspots of poultry production

So far, the most extensive LCA study aiming to quantify the environmental impacts of UK chicken production systems has been carried out in a Defra LINK-funded

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project Poultry LCA[12–15]. This project applied the systems-based LCA model together with detailed production data from poultry industry, and quantified the baseline level of environmental impacts of the main UK broiler and egg production systems. It subsequently identified opportunities where greatest environmental improvements would be possible.

The overall environmental impacts arising from poultry (and other non-ruminant livestock) production can be roughly considered to originate from three separate sources: (1) feed production, (2) direct farm energy use and (3) emissions from housing and manure management. The results of the Poultry LCA project showed that the first category, i.e. feed production, including growing the feed crops and processing and transporting the ingredients, was the main component of several environmental impact categories, most notably the GWP, both in broiler and egg production systems[12,13] (Fig. 1), a result which is consistent with LCA studies form other countries[4,16].

The high contribution of feed production to GWP was affected by the fact that some feed ingredients, especially soya and palm oil, were considered to be partly produced on land that has been only recently converted from natural vegetation to agricultural use in South America and South Asia. In the LCA model, the partial losses of ecosystem carbon storage as a result of such conversion were added to the CO_2 emissions and consequently to the GWP arising from the system. When calculating the LUC effect on GWP, this study applied the guidelines of the carbon footprinting method PAS2050[17]. However, there is not a full international agreement on the method of how to account for LUC in LCA, and this has potentially a very big effect on the estimate of the environment impact of broiler and layer feed and poultry production in general[14,18].

The use of fossil energy in feed production, e.g. for producing fertilisers, field operations and transport also strongly contributed to the environmental impacts categories GWP and Primary Energy Use. Furthermore, the leaching of nutrients and gaseous emissions of nitrous oxide as a result of growing the feed crops had a significant contribution to GWP, AP and especially EP[12,13] (Fig. 1).

The second source of the impacts, direct farm energy use, included the electricity, gas and oil consumed at the broiler production, egg production and breeder farms and hatcheries. The relative contribution of the emissions arising from these activities to the overall impacts varied strongly between production systems, but for example in the case of GWP of the conventional, indoor broiler system, its proportion was <15 %, with the main source being the liquid propane gas used for heating the broiler houses (Fig. 1). In the case of EP and AP, the contribution of farm energy use was minimal. These results demonstrate the fact, that, although reducing farm energy use is often considered as the primary target when aiming improving the environmental friendliness of the system, the effects of such reductions on the overall environmental impacts are actually rather limited[12,13].

The third source of the impacts, namely emissions from housing and manure management, was the main component of AP and had also relatively high contribution to

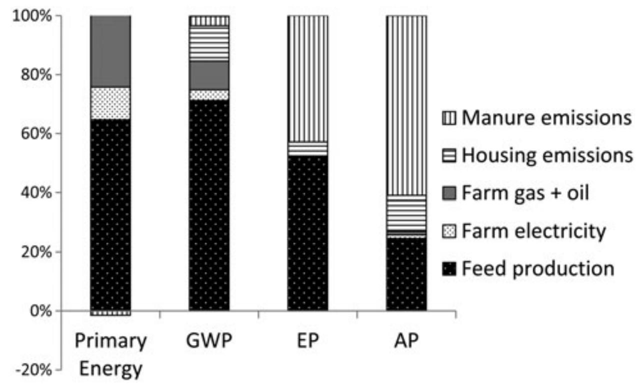

Fig. 1. The relative contribution of different subprocesses to the environmental impact categories Primary Energy Use, global warming potential (GWP), eutrophication potential (EP) and acidification potential (AP) of standard indoor broiler production in the UK[12].

EP both in the broiler and egg production systems (Fig. 1). This was mainly a result of NH_3 emissions, which contributed to both EP and AP, together with nitrate leaching after land application, which affected EP. Housing and manure contributed also to GWP, mainly as a result of nitrous oxide emissions. It should also be noted that poultry manure replaced some of the manufactured fertilisers used in crop production and this effect partially counterbalanced the GHG emissions related to the production[12,13].

The results of Leinonen *et al.*[12,13] also show that the differences in the environmental impacts between different systems in both broiler and egg production were largely related to the efficiency of resource use of the system, although there was also a large variation between farms within each system (Fig. 2). In broilers, the conventional indoor production system which had a shorter production cycle compared with the alternative systems (free range and organic production) was the most efficient in terms of feed conversion, and therefore also had the lowest feed consumption and manure production per kg carcass produced. Also in egg production, the alternative systems (barn, free range, organic) were generally less efficient than the conventional system where hens are kept in cages). As a result, a general trend was found where less intensive poultry systems had higher environmental impacts than more intensive systems.

Probably one of most debated issue of agricultural systems has been the comparison of environmental sustainability of conventional and organic systems of production. Although the organic systems have a relatively low productivity (affecting the environmental impacts per unit of output), this has been compensated at least in part by the low input of resources to the system. The study by Leinonen *et al.*[12,13] found that organic poultry systems have higher AP and EP than other systems considered. However, opposite results have also been observed, showing that organic or other extensive forms of livestock production can reduce the use of fossil fuels, fertilisers and other inputs[19–21] or have lower emissions from housing[22], and therefore they can be equally or less environmentally impacting than intensive systems.

Compared with broiler and chicken egg production, LCA studies on other poultry species have been relatively

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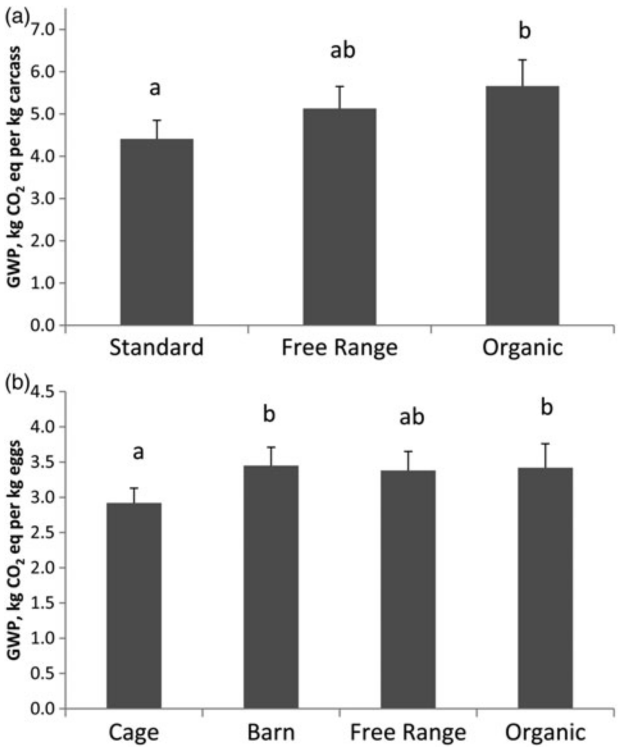

Fig. 2. Global warming potential (GWP; kg CO_2 equivalent per 1 kg expected carcass weight or per 1 kg eggs) for the main UK broiler (a) and egg (b) production systems. Different lowercase letters (a, b) indicate statistically significant differences ($P < 0{\cdot}05$) between the systems[12,13].

rare[5,23]. Recently, in another large scale national research project, Leinonen *et al.*[24] quantified the environmental impacts of the main UK turkey production systems. One of the major differences of turkey production when compared with the broiler systems was that due to considerably longer production cycle, the feed intake and consequently the emissions from housing and manure were higher per produced output (e.g. kg meat). This in turn had a negative effect on the environmental impacts. When comparing different turkey production systems with each other, it was found that systems producing male turkeys had higher feed consumption per unit of output than systems producing females, again as a result of longer production cycle for the latter[24]. Conversely, this was partially compensated by the fact that male birds required less farm energy use per unit of output, due to higher meat output per bird. As a result, together with high variability in production figures between farms, generally the differences in environmental impacts between different turkey systems were small and statistically non-significant[24].

Reducing environmental impact through feed-related activities

As the LCA results of the baseline poultry systems demonstrate, the consumed quantity of feed has a major effect on the overall environmental impacts per unit of product (meat or eggs)[12,13,24]. For example the majority of all GHG emissions related to the poultry production were caused by the growing, processing and transporting broiler, layer and turkey feed. In UK poultry systems, wheat is usually the main component of feed, and soyabean meal is the most important additional protein source, due to its favourable amino acid composition. As mentioned earlier, currently a large part of the soya used as animal feed in the UK is produced in South America, where recent large-scale LUC have occurred, resulting in emissions of GHG to the atmosphere.

In addition to the GHG emissions arising from crop production, feed also has other, either direct or indirect, consequences on the environment. For example, growing feed crops contributes to eutrophication and acidification of the environment, mainly as a result of leaching of nitrate to water and emissions of NH_3 to the atmosphere. Furthermore, the emissions from poultry housing and manure management have a major contribution to these impacts (Fig. 1). The magnitude of these emissions is dependent strongly on the amount of excreted nitrogen, which in turn depends on the feed conversion efficiency of the birds and the protein content of diet. This is a result of the fact that all nitrogen that is not retained in the bird body (in form of protein) will be eventually released to the environment (although some of it can be utilised as crop fertiliser after field spreading of manure).

Thus, there are basically two ways to reduce the feed-related impacts of poultry production. First, improving the feed efficiency, i.e. reducing the amount of feed needed for a certain body weight gain or egg production, would reduce the emissions arising from both feed production and manure management. Second, it should be possible to select feed ingredients that have lower environmental impacts during the production stage, or have more balanced nutrient content, which would reduce the excretion of nutrients such as nitrogen and phosphorous. In an ideal situation, using diets that fulfil both of these criteria would be expected to produce a maximal reduction of the impacts to environment. These strategies are discussed in more detail later.

Improving feed efficiency in poultry systems

There are two strategies to improve the feed efficiency of livestock production. First, it may be possible to improve feed utilisation by processing techniques or by using additives such as enzymes to improve digestion. Second, the energetic efficiency of the animals could by improved, e.g. by means of selective breeding, allowing them to produce a certain amount of output with less energy intake thus reducing the feed consumption. The consequences of both these strategies on environmental sustainability of poultry production are discussed later.

As mentioned earlier, protein sources are probably the most problematic component of poultry feed in terms of their environmental consequences. One suggested method to reduce such emissions is to reduce the required

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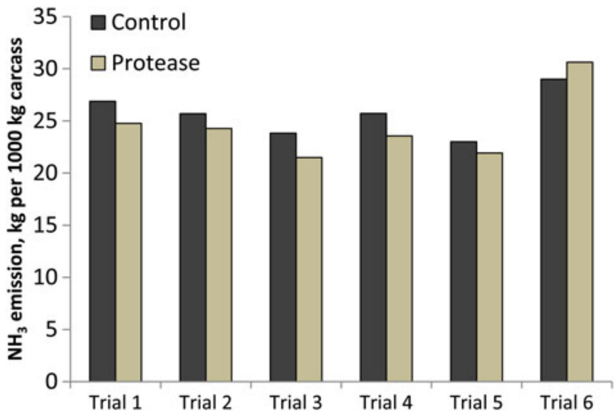

Fig. 3. (Colour online) Emissions of ammonia (NH_3) to air with standard soya-based feed (Standard) and low-protein feed with protease supplement (Protease), kg NH_3 per 1000 kg expected broiler carcass weight. The bird performance data are based on six separate feeding trials[26].

amount of dietary protein (and the nitrogen content of the feed) by adding a specific enzyme, protease, to the feed, aiming to improve the protein utilisation[25]. In a recent study by Leinonen and Williams[26] the environmental consequences of using a certain protease product in broiler diets was investigated by applying LCA modelling together with bird performance data from several feeding experiments. Commonly for all these experiments, the main differences in the broiler feeding programmes with and without protease were the amount of soya needed to be used in the diets. By adding the protease to diet, the required digestible protein intake could be achieved with a smaller proportion of soya in the feed, which resulted in overall reduction of the GWP arising from the feed production (by up to 12 % per mass unit of feed). Furthermore, when the whole broiler production chain was considered by Leinonen and Williams[26], in most feeding experiments that used the enzyme, the largest relative improvements were found in environmental impact categories EP and especially in the AP. The reason for this was that when protease was used in the diets, the crude protein content of the feed could be reduced, which automatically reduced the amount of nitrogen excreted by the birds. This effect reduced the emission of NH_3 which affects both the AP and EP (Fig. 3), and leaching of nitrate, affecting the EP. However, it should be noted that if the low protein diet had any negative effect on bird performance (e.g. reduced growth or increased mortality), the environmental benefit could be easily reduced or completely lost, which was actually the case in one of the experiments analysed (Fig. 3).

Genetic selection has been seen as an alternative option to improve the feed efficiency of animals and therefore also to reduce the environmental impacts of livestock production[27]. In broiler production, the most notable genetic trend during the past decades has been an increase of growth rate and therefore reduction of the time required to reach the slaughter weight[28]. According to the industry, selection to further improve this trait is also expected to continue in the future (I Leinonen, personal communication). A direct consequence of the shortening of the production cycle is that an increasingly higher proportion of the metabolisable energy (ME) obtained by the animal from feed is retained in the body (as protein and lipid) and a smaller proportion is released as heat. It is not clear to what extent traits other than growth rate (e.g. bird activity), have affected the reduction of the bird heat production, but it is quite obvious that the energy requirement of birds has considerably reduced with genetic selection. For example, data from the broiler breeding industry shows that the ME needed for a bird to reach a certain slaughter weight decreased by about 12 % during the years 1995–2009[29]. In practice, this trend has been observed as a smaller feed consumption of the birds[28,30]. Other trends that have likely contributed to improved feed efficiency are improved carcass yield (i.e. a bird with a certain body weight now produces more meat than before) and reduced mortality (as a result of genetics or management).

Earlier studies on this topic[31,32] suggested that the genetic changes and especially the reduced feed consumption have considerably reduced for example the GHG, NH_3 and nitrate emissions arising from poultry production. However, it should be noted that studies so far considering the effects of genetic changes on environmental impacts have been based on rather simplified assumptions, for example expecting that changes in the environmental impacts arising from feed production would be directly proportional to the changes in feed conversion ratio, without trying to understand the mechanisms behind such changes. For more accurate predictions, it might be necessary to apply a more mechanistic modelling approach in order to understand the overall consequences of continuing genetic selection. For example, the shift towards faster (protein) growth and reduced loss of energy as heat may require changes in the feeding practices. This is demonstrated by the following simple example.

In this example, we use the current genotype of a typical broiler bird grown in the UK (Ross 308) as a baseline. According the breeding industry performance objectives[33], one bird would require about 0·6 kg protein and in total about 40 MJ ME in feed to reach a target slaughter weight 2 kg. Following a typical UK least cost feed formulation, these requirements would be met by feeding this bird 2·2 kg wheat and 0·86 kg 'protein crops' (soya meal and rapeseed), together with small amounts of vegetable oil and additives (including pure amino acids). According to the poultry LCA framework[12,13], the GHG emissions arising from the production of these ingredients would be in total 2·88 kg CO_2 equivalent. Now, we assume an arbitrary, but possible scenario where the ME requirement of this bird will be reduced by further 10 % through selective breeding. It would be tempting to assume that this relative reduction could be directly applicable also to the feed consumption and thus to the GHG emissions from feed production. However, this is not the case, since the composition of the feed may also necessarily change as a result of changing requirements of the bird. To grow the 2 kg bird, we should still expect to need the same amount of protein

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in the feed as in the case of the baseline bird (since the protein content of the bird body and thus the protein requirement are not expected to decrease), despite the reduction in the overall ME requirement. As a result, again following the least cost formulation, the feed eaten by this scenario bird would consist of 1·8 kg wheat and 0·97 kg protein crops (plus vegetable oil and additives). Despite the reduction of the overall amount of consumed feed, the GHG emissions arising from this new diet would increase from the baseline value of 2·88 to a higher value of 2·91 kg CO_2 equivalent per bird. This is caused by the required increase of the amounts of protein crops soya and rapeseed in the diet, the production of which is associated with high environmental impacts, including GHG emissions from LUC in the case of soya. This example demonstrates that although genetic selection has the potential to reduce the resources needed for broiler production (including feed consumption), the environmental impacts of certain feed ingredients, most notably protein sources, may limit the benefits of this strategy. Potential solutions for this problem are discussed later.

Changing major feed ingredients in poultry diets

Substituting South American soya meal with alternative protein sources in feed has been usually seen as a major opportunity to reduce the environmental impacts of non-ruminant livestock production systems in Europe. Leinonen *et al.*[14] applied the LCA model to evaluate possible changes in the environmental impacts of UK broiler and egg production with different diet formulations with alternative protein crops as model inputs. In the alternative diets, protein sources grown in Europe, namely beans, peas, rapeseed and sunflower meal, replaced some or most of the soya. In the alternative diets used in the model simulations, the inclusion rates of the ingredients were modified, so that the ME and nutrient content (including essential amino acids lysine, methionine, cystine, tryptophan, threonine, arginine and valine) of the diets remained unchanged. Pure amino acids were added to the diets when needed to maintain the required level of each essential amino acid. This had some effect on the crude protein content of the diets, and for example the bean and pea based diets had a lower level of crude protein than the baseline soya diet.

The results of the LCA model showed that when relatively high inclusion rates of beans or peas (up to 300 g/kg) were used in the diets, the GWP of broiler and egg production could be reduced by up 12 % when compared with the soya-based baseline diet. However with lower, realistic inclusion rates these reductions were much more modest, and when all uncertainties in the calculations were taken into account, it was found that these effects were not statistically significant. One reason for this relatively small effect was the unwanted consequence that when replacing soya with alternative protein crops some wheat had also to be replaced with denser energy sources (e.g. vegetable oils) which have potentially larger environmental impacts than those of the removed wheat. Furthermore, in order to maintain the nutrient balance of the alternative diets, higher amounts of pure amino acids had to be added to alternative diets compared to the original soya diets. Although the amount of these ingredients still remained relatively low, their GHG emissions per unit are high and, as a result, they partly counteracted the favourable effect of soya reduction. It should be also noted that the reduction in GWP strongly depends on the method of LUC accounting applied in the analysis. With an alternative scenario where all soya used in the diets originated from sustainable sources[17], or when indirect LUC was included in the calculations[34], only minimal differences between the different diets were found. In general, the results by Leinonen *et al.*[14] show that there is a potential to reduce the GWP of livestock production by using European protein sources instead of soya in animal feed, but there are limitations in the magnitude of reduction that can be reached through this strategy. This result is consistent with other previously published studies. For example, Baumgartner *et al.*[35] also found a rather limited potential of European legumes to reduce the environmental impacts, when used in livestock feed.

When the effects of alternative poultry diets on other environmental impact categories (in addition to GWP) were considered[14], it was found that the use of beans and peas had only a minor effect on the EP. Nitrate leaching from the growing of beans and peas is relatively high, due to the surplus nitrogen these crops fix directly from the atmosphere, and this increases their overall EP. However, this effect was partly counterbalanced by the crude protein content of feed which was artificially reduced in the diets with European protein crops with high inclusion of pure amino acids. A bigger improvement occurred in AP especially in broiler production, which was reduced by 21 and 15 % when diets with high levels of inclusion of peas and beans were applied, respectively. However, similarly as in the case of EP, this effect only occurred because the alternative protein sources were combined with pure amino acids. In practical farming, inclusion of high levels of pure amino acids may be too expensive, which limits the potential environmental benefits of alternative feed crops.

Another opportunity to replace part of soya in poultry feed is the use of high-protein agricultural co-products, for example (in the case of UK poultry production) wheat-based dried distillers grains with solubles (DDGS) originating from bioethanol production. Although the process of production of these feed ingredients (e.g. bioethanol distillation) may not be very environmentally friendly itself, the potential environmental benefits of such products are based on the principle of economic allocation of the environmental burdens. The starting point of this approach is that all environmental impacts (such as GWP) are distributed to various co-products originating from a certain process in the same proportions as the relative economic values of these products. As a result, less of the burdens should be allocated to DDGS (low economic value) than to bioethanol (high value).

Although economic allocation is not a preferred approach according to international standards for LCA

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such as ISO 14040[9], it is commonly used in agricultural LCA studies, simply because there is no other way for separation of the impacts in biologically based co-products. For example, it is not possible to quantify how much of the inputs to wheat production (e.g. fertilisers) are specifically utilised by the crop to produce soluble carbohydrates (converted to ethanol) or protein (fed to animals as a major component of DDGS). In the Poultry LCA project, the environmental impacts of wheat-based DDGS were quantified from published data by Scacchi *et al.*[36] and used as a part of the LCA model for broiler production. The environmental burdens of bioethanol production are relatively high, and the results of the study showed that the use of DDGS in the diets could not reduce GWP, even when relatively low proportion of the burdens from bioethanol production was allocated to DDGS. Both EP and AP arising from poultry production were clearly higher with the DDGS diet than with the baseline soya-based diet. This was mainly a result of high but imbalanced crude protein content of the DDGS diet causing higher nitrogen excretion rates and higher NH_3 emissions and nitrogen leaching.

An important aspect to note is that the earlier scenarios of changing the poultry diets are based on theoretical calculations assuming that the bird performance would remain unchanged when the alternative diets are used. If any effects on the bird performance occur as a result of changing diets, they may have consequences also on the environmental impacts. For example, poorer feed conversion efficiency would automatically increase the impacts per unit of the final product (i.e. larger amount of feed would need to be produced to produce a certain amount of meat or eggs). Potential increase of mortality would also have similar effects. Higher mortality would mean that a higher proportion of the feed consumed by the birds would be wasted, and therefore more feed is needed to produce equal amount of the output. In addition to feed, mortality would also affect other resources, as the dead birds have also contributed to farm energy consumption. Changes in bird performance would also have effects arising from manure management. It was discussed earlier that the alternative diets could reduce the EP and AP as a result of reduced crude protein content in the feed. This is because relatively small changes in protein intake can have a significant effect on the amount of excreted nitrogen, which in turn would directly affect the emissions to the environment. However, the same effect would also work to the opposite direction. Therefore, even relative small deterioration in feed conversion efficiency could strongly increase the nutrient excretion of the birds and considerably reduce the environmental benefits of alternative diets. These effects were demonstrated in the recent turkey LCA project[24], where turkeys were fed either standard soya-based diet or an alternative diet based on European protein sources (I Leinonen, unpublished results). Although the production of the alternative diet reduced some environmental impacts per mass unit of feed, there was a small deterioration in the performance of the birds fed this diet, and therefore no reduction in the overall impacts of the turkey production chain could be achieved.

Changes in housing and manure management

As discussed earlier, the conventional, usually intensive poultry systems have been generally considered to be environmentally friendly due to their efficiency, i.e. low resource use and low emissions per unit of product[12,13]. This raises the issue of tradeoffs in livestock systems, as usually intensive systems of production are also perceived as having reduced animal welfare. In a study carried out by Leinonen *et al.*[15] the environmental consequences of new, animal welfare enhancing production systems that have recently been introduced to broiler and egg production in the EU were quantified. The data for this study were collected from the UK broiler and egg production industry, and used as an input of the systems-based LCA model. The analysis covered both the conventional main production systems (standard indoor broilers and cage eggs) and new systems including colony cage egg production and low stocking density broilers.

In the low-density broiler system, the maximum live weight per square metre was reduced from the standard practice of the industry, following the requirements of certain retailers. In some of the low-density systems, an additional feature was a heat exchanger, which was used to circulate the heat otherwise lost in ventilation, in order to compensate the expected increase of heating requirement (as a result of the fact that a smaller number of birds in a house produces less heat). In the egg production, the traditional battery cage system was replaced by a new, lower density colony cage system, following the changes in EU legislation.

The results showed that the low-density broiler system increased the Primary Energy Use and GWP, mainly due to increased liquid propane gas consumption during housing as a result of increased heating requirement. However, the increase of farm energy use was partly compensated by reduced feed intake per unit of broiler meat produced and by a shorter production cycle used in this system. As a combined effect of these changes, the overall increase of GWP was only 2 %, when the low-density system was compared with the baseline system. When the heat exchanger was applied in the low-density system, the overall primary energy use in applying the heat exchanger was similar to the baseline system, and the GWP was actually reduced by 3 %. This was a combined effect of only moderately increased liquid propane gas consumption and improved feed efficiency. Both alternative systems resulted in reduction in the EP (by up to 8 %) and AP (by up to 10 %). This was mainly caused by higher feed efficiency compared with the baseline system[15].

The results for different egg production scenarios showed that the colony cage system had 8 % lower primary energy use and 3 % lower GWP than the baseline battery cage system, due to lower energy use in housing and slightly improved productivity. There were only minor differences in the EP and AP between the systems, as there were no significant changes in feed consumption or nutrient excretion per unit of product, when the conventional cage system was replaced by the colony cages. In general, the results for both broiler and egg production systems suggest that measures taken to improve bird welfare in poultry production have had no major effect on the efficiency of the system. The application of new technologies can actually improve both the economic and environmental sustainability of such systems, in addition to improving welfare[15].

As discussed early, a large proportion of the eutrophication and especially acidification arising from poultry systems originates from housing and manure management. These emissions can be reduced for example by improving the feed efficiency, but it can be expected that direct measures aiming to improve the management of manure both at the farm and in connection with its end use could also reduce those emissions. Currently a common practice is to spread the manure directly to the field as a crop fertiliser. Although this has some environmental benefits, i.e. it can reduce the demand of production of synthetic fertilisers and also increases the soil carbon storage (thus removes CO_2 from the atmosphere), the problem of this practice is considerable emissions of NH_3 and nitrate to the environment. Therefore, alternative strategies for manure management have been considered[37]. One of the most promising new practices is the use of poultry litter (i.e. manure + bedding) as a fuel to generate electricity at a power station. Based on a recent study by Williams *et al.*[38], the fuel use of litter (instead of direct field spreading) can reduce the primary energy use (as a result of reduced need of fossil fuels in electricity generation) and can result in a considerable reduction of nitrogen emissions from the field thus having a beneficial effect on EP and especially AP. Furthermore, the main mineral nutrients (e.g. P and K) would remain in the ash after combustion and would still be available for the use as fertiliser.

Conclusions

Environmental sustainability of agricultural production and especially livestock systems is a complex issue and any attempts to make improvement in this area require understanding of a network of multiple interactions, ranging from the resources used for feed crop production to the end use of manure. LCA provides a useful tool to systematically handle such interactions and consequently identify where significant improvements can be made to the sustainability of livestock systems. The results presented here represent so far the most extensive assessment of the environmental sustainability of the UK poultry industry. They demonstrate that although poultry systems are generally more environmentally friendly than many other livestock systems, there are still opportunities to reduce the environmental impacts of poultry production, for example through a combination of changing feeding strategies, genetic selection and improvements in housing and manure management.

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Conflicts of Interest

None.

Authorship

Both authors contributed to the writing of this paper.

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