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The potential to reduce environmental impacts of poultry production systems by including alternative protein crops in their diet: a quantitative comparison with uncertainty analysis

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ABSTRACT

The effect of including different protein sources in poultry diets on the environmental impacts Global Warming Potential (GWP), Eutrophication Potential (EP) and Acidification Potential (AP) of typical UK broiler meat and egg production systems was quantified using the Life Cycle Assessment (LCA) method. The broiler and layer diets compared in the study were either standard soya-based, or alternative diets based on European-grown protein crops, including field beans, field peas, sunflower meal and whole rapeseed. Different methods for accounting for land use change (LUC) in feed crop production were applied, including 1) a weighted average of "new" and "mature" agricultural land used for soya production ("best estimate" scenario), 2) assuming no LUC in the production of soya used in these diets ("sustainable soya" scenario) and 3) including indirect LUC for all arable crop production ("top-down" scenario). Monte Carlo simulations were used to quantify uncertainties in predicted impacts and to perform statistical comparisons between the effects of different diet compositions. The results showed that when included at relatively high levels in the diets (up to 30% by mass), peas, beans and rapeseed could slightly reduce the GWP (up to 12%) of broiler meat and egg production. However, when uncertainties in the data were taken into account, these reductions were not statistically significant. Furthermore, the reduction in GWP strongly depended on the method of LUC accounting applied in the analysis. With the "sustainable soya" and "top-down" scenarios, only small, non-significant differences between the different diets were found. In the case of EP, only small non-significant changes could be achieved with the alternative protein sources. For AP, a reduction of more than 20% could be achieved if the crude protein content of the diets was reduced by using beans or peas in combination with pure amino acids. This study demonstrates the importance of a holistic approach, coupled with Monte Carlo uncertainty analysis, to evaluate the environmental impacts of livestock systems. It takes into account the environmental burdens related, for

example, to feed production and transport and differences in emissions from housing and the end use of the manure.

Key words: Broiler production, egg production, soya, global warming potential, land use change, Life Cycle Assessment

1. Introduction

The production, processing and transport of feed has been found to be one of the main sources of environmental impacts and especially greenhouse gas (GHG) emissions in several livestock production systems (e.g. Eriksson et al., 2005; van der Werf, 2005; Pelletier et al., 2008; Leinonen et al., 2012a, 2012b). Furthermore, one of biggest sources of GHG emissions arising from feed is related to the production and processing of soya, which is globally used as the main protein source in livestock production (FAO, 2002). The cultivation of soya is associated with recent land use changes (LUC), which cause GHG emissions from deforestation and conversion of other land uses to arable land, with a loss of carbon previously stored in soil and biomass (e.g. Guo et al., 2002); it also causes a loss of biodiversity (WWF, 2011).

Substituting soya with alternative protein sources in feed can be expected to reduce the environmental impacts of poultry or pig systems. This applies particularly to crops grown on land where no recent LUC from natural vegetation to arable land has occurred. This is broadly the case in Western Europe, where feed crops including protein sources are generally grown on mature agricultural land. In Europe, the most recent large-scale LUC occurred during and shortly after the Second World War (e.g. Houghton et al., 1983); therefore, the land has had decades to stabilise. In addition to LUC, changes in management practices may also affect the carbon content of arable soil (e.g. Jenkinson et al., 1990). However, such changes are difficult to quantify, and they are not currently included in guidelines for calculating the soil GHG emissions, such as PAS 2050 (BSI, 2011). Therefore, when quantifying environmental impacts of arable production, it is generally assumed that in Western Europe no current emissions of GHG occur as a result of changes in soil carbon content.

A systematic, quantitative approach is needed to evaluate the environmental impacts in complex agricultural systems, such as broiler meat and egg production. A method called Life Cycle Assessment (LCA) is generally preferred, since it accounts for all environmental burdens occurring during the production cycle, starting from raw material extraction through to the end products (BSI, 2006). Several indicators of environmental impacts are commonly used, including resource use and potential for causing harm to ecosystems and humans, including global warming from GHG emissions and eutrophication from nitrate (NO_3^-) and phosphate (PO_4^{3-}) leaching. A holistic approach, such as LCA, is very especially useful when evaluating the effect of environmental impacts of different feed ingredients on livestock production (e.g. et al. Nguyen, 2012; Meul et al., 2012).

LCA has been applied in agricultural studies for example to calculate overall environmental impacts of animal production in different countries (e.g. Nguyen et al. 2010; Webb et al., 2012), to compare the impacts of different systems of production (e.g. Cederberg and Mattsson, 2000; Williams et al., 2006; Thomassen et al., 2008; de Vries and de Boer, 2010) and to evaluate potential reduction in impacts using alternative diets (e.g. Eriksson et al., 2005; Nguyen et al., 2012). However, comparison of different LCA studies is not always straightforward, since differences may occur in functional units, system boundaries, emission factors used, and in the methodology in general (Leinonen et al. 2012a). In the case of agricultural LCA studies, one of the major questions is whether or not the potential LUC due to crop production should be taken into account and, if so, what method should be used to quantify the effects of such changes. Furthermore, the inputs of LCA models also include other uncertainties (e.g. potential measurement errors, variation in activity and production data). The effects of these uncertainties on the model output must be quantified in order to make it possible to evaluate the statistical significance of the differences between the scenarios under consideration.

The objective of this study was to apply LCA modelling to quantify changes in a set of environmental impacts, including Global Warming Potential (GWP), Acidification Potential (AP) and Eutrophication Potential (EP), arising from the substitution of soya based diets by alternative protein sources produced in Europe. The assessment was made for the two main poultry systems in the UK, namely standard indoor broiler and free range egg production. The alternative protein sources included field beans, field peas, sunflower meal and whole rapeseed. Furthermore, in comparing different diets, alternative methods were used to address LUC effects and associated GHG emissions due to the production of soya meal. The study quantified the level of uncertainties in the model predictions, which would allow statistical comparison between the different scenarios.

2. Methods

2.1. Systems approach

The approach taken in the current study was systems modelling of production as described by Williams et al. (2006, 2007, 2010). This included structural models of the industry, process models and simulation models that were unified in the systems approach so that changes in one area caused consistent interactions elsewhere. This approach was applied to both feed crop and animal production. The systems modelled in this study included crop production, non-crop nutrient production, feed processing, breeding, broiler and egg production (including farm energy and water use and gaseous emissions from housing), and manure and general waste management, as described by Williams et al (2006) and applied to poultry systems by Leinonen et al. (2012a, 2012b).

The production systems (indoor broiler, free range laying) in this study were considered to represent typical UK egg and broiler production as described by Leinonen et al. (2012a, 2012b). Farm energy consumption for heating, lighting, ventilation and feeding was based on average data from typical farms provided by the industry. Information about the type and amount of bedding was also obtained from the industry. Additional data, such as the life cycle inventories (LCI) of agricultural buildings and machinery, came from Williams et al. (2006). The same farm data was applied for all feeding scenarios within each system (broilers, eggs) included in this study.

2.2. Production model

The structural model for broiler and egg systems calculated all of the inputs required to produce the functional unit (either 1000 kg of expected edible carcass weight for broilers or 1000 kg marketable eggs), allowing for breeding overheads, mortalities and productivity levels. It also calculated the outputs, both useful (broilers, eggs and spent hens) and unwanted (e.g. wastes and mortalities). In the model, changes in the proportion of any activity must result in changes to the proportions of others to keep producing the desired amount of output. Establishing how much of each activity was required was found by solving linear equations that described the relationships that linked the activities together.

Mechanistic animal growth, production and feed intake models were used in the current study to calculate the total consumption of each feed ingredient during the whole production cycle, and to calculate the amounts of main plant nutrients, nitrogen (N), phosphorus (P) and potassium (K) in manure produced by the birds during the production cycle. The model, described by Leinonen et al. (2012a, 2012b), was based on the principles presented by Emmans and Kyriazakis (2001) and Wellock et al. (2003) and predicted the daily feed intake of a single bird as a function of feed composition and bird energy and protein requirements. This included requirements for both production (body growth and eggs) and maintenance. The model was calibrated to match real production and feed intake data, provided by the broiler and egg industry for different systems (Leinonen et al. 2012a, 2012b), by adjusting the model parameters for growth rate, energy requirement for maintenance and egg production.

The model calculated the N, P and K contents of the manure according to the mass balance principle, i.e. the nutrients retained both in the animal body and eggs were subtracted from the total amount of nutrients obtained from the feed (including the additional nutrients obtained from foraging in free range egg production). In addition to the nutrients excreted by the birds, nutrients in the spilled feed and uncollected eggs were added to the manure in the calculations. For the purpose of the study, it was assumed that all broiler, pullet, layer and breeder manure was used for soil improvement as a fertiliser, excluding the proportion that was excreted outside in the free range egg production system (see Section 2.3).

2.3. Crop and manure sub-models

A separate sub-model for arable production was used to quantify the environmental impacts of the main feed ingredients, with main features as in Williams et al. (2010). All major crops used for production of poultry feed were modelled. For the crops produced overseas (maize, soya, sunflower, palm oil), the production was modelled as closely as possible using local techniques. Transport burdens for importing overseas crops and burdens from processing the feed were also included.

The current study followed the principles of Audsley et al. (1997) and Williams et al. (2006, 2010), taking a long-term approach to agriculture, for example ensuring that N emissions and uptake from manure are accounted for on an infinite time horizon. This differs from the shorter term methods that are often applied in more empirically-based carbon footprinting (e.g. BSI, 2011). This tends to result in lower net burdens from manure, because the birds receive credits from the plant nutrients in manure, both by displacing manufactured fertilisers and reducing land occupation by increasing yields.

Poultry manure is a source of direct gaseous emissions of ammonia (NH_3), nitrous oxide (N_2O) and to a lesser extent methane (CH_4), which occur during housing, storage and land-spreading and were quantified with a separate manure sub-model. Emissions of NH_3, N_2O and CH_4 arising from excreta during housing were calculated following the methods of Williams et al. (2006), which are based on UK national inventories (Chadwick et al., 1997; IPCC, 2006; Misselbrook et al., 2008; Sneddon et al., 2008), emission factors and methods. Manure management also uses energy and these burdens were debited against the poultry (along with burdens from direct gaseous emissions). In the model, all of the nutrients applied to the soil as manure were accounted for as either crop products or as losses to the environment (Sandars et al., 2003). The benefits of plant nutrients (N, P and K) remaining in soil after land application were credited to poultry by offsetting the need to apply fertiliser to winter wheat as described by Sandars et al. (2003) and implemented by Williams et al. (2006). However, the nutrients excreted outside the house in the free range egg production system (assumed to be 10% of the total excreted nutrients) were not credited to crop production as the entire ranging area was determined to be grassland, and was not used for growing commercial crops (which is a common practice in UK non-organic free range egg production).

2.4. Environmental impacts

Emissions to the environment were aggregated into environmentally functional groups as follows:

Global Warming Potential (GWP). The main sources of GWP in the poultry industry are carbon dioxide (CO_2) from fossil fuel, N_2O and CH_4. GWP was quantified in terms of CO_2 equivalents: with a 100-year timescale 1 kg CH_4 and N_2O are equivalent to 25 and 298 kg CO_2 respectively (IPCC, 2006).

Eutrophication Potential (EP). EP was calculated using the method of the Institute of Environmental Sciences (CML) at Leiden University (http://www.leidenuniv.nl/interfac/cml/ssp/index.html). The main sources are NO_3^- and PO_4^{3-}

leaching to water and NH_3 emissions to air. EP was quantified in terms of PO_4^{3-} equivalents: 1 kg NO_3-N and NH_3-N are equivalent to 0.44 and 0.43 kg PO_4^{3-}, respectively.

Acidification Potential (AP). AP was also calculated using the method of the CML The main source in the poultry industry is NH_3 emissions, along with sulphur dioxide (SO_2) from fossil fuel combustion. NH_3 contributes to AP despite being alkaline; when emitted to the atmosphere it is oxidized to nitric acid. AP was quantified in terms of SO_2 equivalents: 1 kg NH_3-N is equivalent to 2.3 kg SO_2.

2.5. Diets considered

The baseline, soya meal based diets representative of those used in the UK were constructed using information provided by the industry (Tables 1,2; Leinonen et al., 2012a, 2012b). Broiler diets changed four times during the growing period and layer diets changed five times during the whole cycle according to common practice. The alternative protein sources (beans, peas, sunflower and rapeseed) replaced some soya in the different alternative broiler and layer diets. Beans, peas and rapeseed were included whole, whereas sunflower was included as a meal. Since rapeseed was already included in the baseline broiler diet and sunflower in the baseline layer diet, separate alternative diets based on these ingredients for these systems were not used in the analyses.

Two levels of each alternative ingredient were applied in separate diets, i.e. “realistic” and “extreme”. The realistic inclusion rates were based on suggestions from the poultry industry, and represented levels that could practically be used or are already in use in commercial poultry production. The extreme inclusion rates represented a theoretical maximum for each ingredient (e.g. Farrell et al., 1999; Perez-Maldonado et al., 1999; Rama Rao et al., 2006) and were used in this study to quantify the sensitivity of environmental impacts to changes in inclusion rates of each alternative ingredient. The inclusion rates of other ingredients were modified so that the metabolisable energy and nutrient content of the diets remained unchanged. For protein, this requirement was applied to the main essential amino acids, namely lysine, methionine, cystine, tryptophan, threonine, arginine and valine. Pure amino acids were added to the diets when needed to maintain the required level of each. As a result, although the amounts of the essential amino acids were the same for all diets, the levels of non-essential amino acids (and therefore also the crude protein content) could slightly vary between the diets (see Supplementary material). The assumption was made that the level of production and feed intake remained unchanged when the alternative diets were used.

In the alternative broiler diets (Table 1), the inclusion rate of beans varied from 5% (starter diet) to 10% (finisher and withdrawal diets) in the realistic scenario and from 10% to 20%, respectively, in the extreme scenario during the production cycle. For peas, the inclusion rate ranged, respectively, from 7.5% to 20% (realistic) and from 10% to 30% (extreme) and for sunflower from 2.5% to 5% (realistic) and from 5% to 10% (extreme).

[Table 1 here]

In the layer diets (Table 2), the inclusion rate of beans varied from 7.5% (starter diet) to 10% (all other phases) in the realistic scenario and from 10% to 20%, respectively, in the extreme scenario during the production cycle. For peas, the inclusion rate ranged, respectively, from 7.5% to 10% (realistic) and from 15% to 20% (extreme). For rapeseed, the inclusion rate of 5% was applied in all phases of the realistic diet and 10% in the extreme diet.

[Table 2 here]

2.6. Land use change

According to a widely accepted carbon footprinting method, PAS 2050 (BSI 2011), the direct GHG emissions resulting from recent LUC for crop production must be included in the carbon footprint of each crop (i.e. the sum of the GHG emissions per unit mass of crop). Most GHG emissions from LUC are as CO_2 from loss of soil and biomass carbon. "Recent" LUC is defined as occurring in the past 20 years in PAS 2050 (BSI, 2011). This time period is arbitrary, given the non-linear rates of change in soil carbon, but is considered to be a pragmatic value that covers the largest change and the time during which the change is nearly linear. We define land in which LUC has occurred for more than 20 years ago as being "mature". The main land use changes that cause GHG emissions related to soya production are from forest or pasture (natural or managed) to arable land. The pasture is mainly Cerrado in Brazil and Pampa in Argentina (FAO, 2011).

PAS 2050:2011 also states that "Where the country of production is known, but the former land use is not known, the GHG emissions arising from land use change shall be the estimate of average emissions from the land use change for that crop in that country". In this study, a weighted average for soya was derived from an analysis of land use and crop production statistics of the United Nations Food and Agricultural Organization (FAO, 2011). The data were analysed to estimate to rates of change of types of land use and the degree of interchange between crops, in that some soya expansion is from existing arable land. This was used to estimate the proportions of soya grown on mature arable land and that converted from pasture, forest or other land in Brazil and Argentina. LUC emissions were amortised over 20 years for each unit area of land, as in Audsley, et al. (2010). Annual rates of LUC emissions taken from PAS 2050 (BSI, 2011) were combined with the national yields of soya reported by FAO (2011) to obtain LUC emissions per unit mass of soya. This approach was defined as the "best estimate" scenario, and is described in detail in the Supplementary Material. As the overall result of the analysis, the LUC effect of 1.3 kg CO_2e kg^{-1} was included in the GWP per 1 kg of soya meal.

Two alternative approaches to the "best estimate" land use scenario described above were also considered. First, it was assumed that all soya used in the diets of this study came from "mature" agricultural land with no associated direct LUC emissions (defined as "sustainable soya" scenario). Such an assumption is justified as it can be related to real situations, for example North American soya or land with defined and certified history (as required by organic standards for example). It must be recognised that this supply may be more limited than average soya on the international commodity market.

The second alternative approach applied for land use change in this study considered also indirect LUC related to crop production. This is not taken into account by either the "best estimate" or the "sustainable soya" methods and not included in the PAS 2050 specification. It can be argued that all agricultural activity has indirect LUC effects (i.e. growing more of any crop in any economically-connected location in order to meet global demand will increase the land use pressure elsewhere). Thus the LUC emissions should be equal for all crops per ha, and not dependent on their actual location. This approach, known as the "top-down" scenario (Audsley et al., 2009), was also applied in this study. According to this scenario, equal LUC emissions of 1430 kg CO_2 ha^{-1} y^{-1} were included in the production of all crops, regardless the country of their origin or the previous land use (Audsley et al., 2009). The GWP from LUC per kg of each feed ingredient was thus dependent on the land area required for its production, so for example crops with high yield per ha had lower LUC emissions than crops with low yield.

2.7. Uncertainty analysis

Uncertainties in model input data must be taken into account when evaluating differences between the scenarios under consideration. These uncertainties can be divided into two groups, namely “alpha” and “beta” errors (Wiltshire et al., 2009). The alpha errors are considered to vary between scenarios (e.g. variation in animal performance) and therefore should be taken into account in statistical analyses, while the beta errors (e.g. uncertainty in emission factors for N_2O and CH_4) can be assumed to be the same for all scenarios, and therefore to have no impact when scenarios are compared with each other. In this study, the majority of the input data for all scenarios in both broiler and egg systems was identical, and therefore the only errors included in the uncertainty analysis were the alpha errors related to 1) animal performance and feed intake and resulting nutrient excretion, and 2) environmental impacts of production, processing and transport of the feed. The magnitude and distribution of these errors were taken directly from Leinonen et al. (2012a, 2012b), and a Monte Carlo approach was applied to quantify uncertainties in the model outputs. The LCA model was run 1000 times, and during each run a value of each input variable was randomly selected from the predetermined distribution for this variable. The shapes of the distributions were either normal (e.g. biological parameters), lognormal (e.g. emission factors) or triangular (e.g. farm energy use) (Leinonen, 2012a, 2012b). In the simulations, the mechanistic animal model automatically included functional relationships related to animal performance and feed intake. For example, the variation in nutrient intake also resulted in variation in the nutrient content of the manure. The final outcome of the uncertainty analysis was the Coefficient of Variation (CoV, i.e. standard deviation divided by the mean) of each environmental impact category, and this was used to evaluate the statistical significance of the differences between the feed scenarios at 5% probability level, as described by Leinonen et al. (2012a, 2012b).

3. Results and discussion

3.1. Effects of alternative protein sources on GWP

When LUC emissions were calculated by the "best estimate" method, the bean- and pea-based broiler diets reduced the GWP by up to 8 and 12% in the "realistic" and extreme" diets, respectively, compared to the baseline soya diets (Table 3). No reduction in GWP compared to the baseline was found with the sunflower broiler diets (Table 3). In the case of egg production, the diets with beans, peas and rapeseed also resulted in a trend of reduction in GWP with the "best estimate" scenario (Table 3). At the "realistic" level, the use of these ingredients reduced the GWP by 4%, whilst with the "extreme" inclusion levels, beans reduced the GWP by 11%, peas by 9% and rapeseed by 7%. A large part of these GHG emission reductions was caused by the fact that the European crops did not incur GHG emissions from LUC in the calculations. Although the trend of these findings suggest that reduction of GHG emissions with alternative protein source is possible, no statistically significant differences ($P<0.05$) in the GWP of broilers or eggs were found between the "best estimate" soya based and alternative diets when the uncertainties in the model inputs were taken into account in the Monte Carlo simulation.

The exclusion of the direct LUC emissions from soya ("sustainable soya" scenario) had alone a larger effect on GHG emissions than replacing part of soya with alternative protein sources in the "best estimate" scenario. For the baseline soya based diets, this scenario showed a reduction in the GWP of 13% and 18% for eggs and broilers, respectively, when compared to the baseline diets in the "best estimate" scenario. When the "sustainable soya" scenario was applied for all diets (Table 3), the differences in GWP between the alternative protein and the baseline diets were small and non-significant ($P<0.05$). With the bean and pea diets, only up to 1% reduction in the GWP for broilers and eggs occurred compared to the baseline soya diet. This result may appear surprising, since even without the LUC effect, the production and transport of soya meal still resulted in considerably higher GHG emissions than the production of equal amounts of beans or peas. However, without the LUC effect, the contribution of soya represents a relatively small proportion of the overall GHG emissions of broiler and egg production. For example, in the realistic bean diet for layers, the amount of "sustainable" soya removed from the original diet contributed less than 6% to the overall GWP per kg of feed, and an even smaller percentage to the GWP of the whole production system. Furthermore, beans and peas replaced not only soya in the diets, but also part of the wheat to allow high inclusion rates of these alternative ingredients. The metabolisable energy of the removed wheat had to be replaced using other ingredients, and this replacement did not reduce the GWP. In general, to maintain the nutrient and energy balance of the diets, higher amounts of pure amino acids and vegetable oil blend had to be added to bean and pea 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 counteracted the favourable effect of soya reduction.

With the rapeseed layer diets (both realistic and extreme), the GWP was reduced by about 2% compared to the soya diets when the LUC effect was excluded (“sustainable soya” scenario), i.e. that diet was slightly more favourable than the bean and pea diets (Table 3). Again, this may look surprising since GHG emissions from rapeseed production were higher than those of beans and peas, and even higher than those of “sustainable” soya meal. Therefore, one could expect that replacing the soya with whole rapeseed would actually increase the GWP of the feed. However, due to suitable nutrient and energy balance, there is no need to add more pure amino acids to the rapeseed diet than are added to the original soya diet, and the amount of vegetable oil added (which has high environmental burden, partly due to the inclusion of palm oil) in the diet can be substantially reduced. For the broiler diet with sunflower meal, this situation was reversed. More vegetable oil had to be added to the diets because of the low energy content of sunflower meal, and this partially affected the overall increase in GWP.

When the effects of the indirect LUC were taken into account (“top-down” scenario), the GWP of the baseline soya diets was about 5% lower in broilers and 1% lower in eggs compared to the “best estimate” scenario (Table 3). However, for example, in the case of broilers, this figure was still 16% higher than the “sustainable soya” scenario, indicating the large effect of LUC on GHG emissions from poultry production. The differences between the baseline soya based and the alternative diets were small in the “top-down” scenario (as in the “sustainable soya” scenario) and no statistically significant differences could be found, when the uncertainties in the inputs were taken into account. For example in broilers, the changes in GWP varied from a 2% reduction (extreme pea diet) to a 1% increase (sunflower diet), and in eggs from a 1% reduction (extreme bean and pea diets) to a 1% increase (rapeseed diet).

[Table 3 here]

All approaches to calculating LUC applied in this study have legitimacy and the results clearly indicate that this effect cannot be ignored in the environmental assessment of livestock production. The widely accepted application of PAS 2050 means that in many studies using the approach of this specification, only the direct LUC emissions are included in the GWP of agricultural commodities. This approach can, however, create some oddities. For example, the use of organic soya from China, as is used in some UK poultry systems (Leinonen et al., 2012a, 2012b), would not incur LUC emissions using the PAS 2050 approach. China is, however, a major importer of non-organic soya from South America, so that organic soya is grown for export displaces domestic production and increases imports from South America. Thus, an increasing demand for organic soya will lead to more pressure on LUC in South America. In general, partly related to different methods for estimating LUC effect, there is a huge range of variation in current estimates of the GHG emissions related to production of essential ingredients of animal feeds, and especially soya, as demonstrated by Prudêncio da Silva et al. (2010). As the results of the current study demonstrate, the conclusion of how much the GWP of animal production systems can be reduced by reducing the soya in diets depends greatly on the estimated contribution of soya in the baseline scenario. The importance of the LUC accounting method was also demonstrated by Meul et al. (2013) who calculated the GWP of pig diets with or without indirect LUC in feed crop production. However, in their study, the estimated direct LUC-related GHG emissions of soya productions were considerable lower than in the present study, where the proportion of soya from different types land use history was derived from FAO statistics. All these methodological differences between studies demonstrate that more research is needed into both improving the estimation of both direct and indirect LUC emissions and establishing the links between changing agricultural activities and rates of LUC across the world. This should lead to a consensus on the best way of addressing this in LCA.

In an earlier study, Nguyen et al. (2012) evaluated the possibilities of reducing the environmental impact of poultry feed with alternative diet formulations. In their study, the GWP per 1 kg of layer feed could be reduced by up to 3% when part of the soya in the standard “least cost” diet was replaced with rapeseed and corn gluten meal. For broiler feed, the maximum reduction was 11%. Keeping in mind the fact that the environmental impacts arising from the feed are only one part of the overall impacts of poultry production, the potential reduction in GWP calculated by Nguyen et al. (2012) is lower than that observed in the present results with the “best estimate” scenario (where the direct LUC effect was taken into account). The main reason for this difference is the estimates of emissions related to production of some of the feed ingredients, most notably soya. In Nguyen et al. (2012), the LUC effect of soya production is lower than in the current study, and therefore the GWP of the baseline “least cost” diet is also relatively low; so, high reductions in this impact category are not possible. In fact, in the “sustainable soya” scenario of the present study, where no LUC effect is included in the soya production, the results of GWP are closer to the results of Nguyen et al. (2012).

Results similar to these in our study have been found in other animal production systems. For example, Eriksson et al. (2005) evaluated the use of alternative protein sources, including peas and rapeseed cake in Swedish pig production. Their results suggested that the pea/rapeseed diet could reduce the GWP from pig production by about 10%, which is close to the “best estimate” predictions for broilers and eggs in the present study.

It is concluded that some reduction in the GWP of broiler and egg production systems may be possible when some of the soya meal of diets is replaced with alternative protein sources. The magnitude of these reductions will depend mainly on the method used to calculate the emissions arising from soya cultivation and related land use changes.

3.2. Effects of alterative protein sources on EP and AP

The different methods for accounting for LUC had no effect on the eutrophication and acidification potentials, and therefore the results presented below are valid for all three LUC scenarios applied in this study. The diets based on European protein sources had only a minor effect on the EP of broilers and eggs, and no statically significant differences between these diets and the baseline soya diet could be found (Table 4). Nutrient leaching from the growing of beans, peas and especially rapeseed is relatively high, which increases the overall EP. However, this effect was partly counterbalanced by the crude protein content of feed being slightly lower in the diets with European protein crops than in the baseline soya diet. This resulted from the high inclusion of pure amino acids in the alternative diets, which allowed attainment of a more balanced amino acid profile of the feed. However, it should be noted than 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. It should also be noted that the crude protein content of feed also has an effect on the GWP (see above) through the level of N_2O emissions arising from housing and end use of manure. On the other hand, the excess N in manure has a fertiliser value, and it can partially reduce the use of synthetic fertilisers and the energy consumption related to their production and decreases environmental impacts.

[Table 4 here]

AP was reduced by 21% and 15% in broilers and 6% and 8% in eggs when high ("extreme") inclusion of peas and beans was applied, respectively (Table 5). However, only the extreme pea diet for broilers was significantly different ($P<0.05$) from the baseline soya diet. There are two reasons for the potential reduction of AP when using the alternative diets. First, when the inclusion of soya is lowered, the SO_2 emissions caused by long transport distances of soya could be reduced. Second, as with EP, the higher inclusion of pure amino acids in pea and bean diets improved the essential amino acid profile. This reduced the overall dietary crude protein concentration, hence reducing the nitrogen excreted in manure and, ultimately, the NH_3 emissions. With the rapeseed diets in egg production, both the acidification caused by feed production and by emissions from layer manure were slightly higher than those in the bean and pea diets, and therefore no or only a minor (non-significant) reduction of the overall AP could be achieved compared to the soya diet. In broiler production, the sunflower diets had only a moderate (non-significant) effect on the AP.

[Table 5 here]

In general, in the case of AP, the effects of alternative protein sources show a similar trend as in the Swedish pig study (Eriksson et al., 2005). Their study also showed that the AP can be reduced if pure amino acids are applied together with alternative protein crops, due to reduction in the crude protein content of the feed. Furthermore, with high inclusion of peas without additional pure amino acids, the AP actually increased in their study compared to the baseline soya diet. Unlike in the present study, Eriksson et al (2005) also found a reduction in EP when using alternative crops with pure amino acids. In an earlier study for poultry feed

(Nguyen et al., 2012), a moderate reduction in EP could be reached when replacing soya with alternative protein sources. However, in some cases this reduction was associated with a simultaneous increase in AP.

3.3. Uncertainties in model predictions

Quantitative comparison based on statistical analyses of different scenarios is not possible if the range of uncertainty of the results is not available. However, despite their essential role in systems comparison, systematic and quantitative uncertainly analyses have very rarely been applied in LCA studies of agricultural commodities. Analytical methods, such as partial differential equations should ideally be used to quantify the uncertainty in modelling analyses (e.g. Leinonen et al., 2006). However, the models used in agricultural LCA are generally complex, they may include several sub-models and a large number of parameters and input variables which have their own uncertainties. Therefore, it may not be practical to apply any analytical methods for such studies. So, uncertainty analysis based on Monte Carlo simulation was used for the present study.

Wiltshire et al. (2009) developed a statistical framework, using Monte Carlo simulation, for quantifying the uncertainties in GHG emissions from food production. This method was applied for all environmental impact categories in the presents study. It was applied similarly in earlier studies of broiler and egg production (Leinonen et al., 2012a, 2012b). The first step when using this method is to quantify the errors associated with each parameter and input variable, and to define their probability distribution functions. In the present study, errors related to the main input variables were based directly on data provided by the UK broiler and egg production industry, and the errors in the emissions factors were based on values obtained from literature (e.g. IPPC, 2006) . When the distribution of each input is known, the Monte Carlo method can be applied to randomly select values of the inputs for each separate simulation, and to produce the probability distributions of the outputs, which are needed for statistical comparison of the scenarios.

However, as demonstrated by Leinonen et al. (2012b), it is important to notice that in many cases the errors related to the a certain variable within a certain scenario are not independent from errors of other variables, or errors of the same variable within the other scenarios. These internal correlations between the errors must be taken into account to avoid systematic misinterpretation of the total uncertainty applied in the system comparison. This was overcome by not sampling correlated variables independently.

When the differences between the scenarios are analysed statistically, only those errors that vary between different scenarios under consideration should be included in the Monte Carlo simulations (alpha errors), and those errors that can be considered identical for all scenarios (beta errors) should be excluded. Examples of the beta errors are uncertainties related to emission factors from housing and manure management and parameters of the animal production model. In the simulations, it is assumed that any error related to these model inputs has a similar effect with the same direction in all scenarios under consideration, and therefore these errors do not affect the possible differences between the scenarios.

Furthermore, variations in some of the different input variables can be correlated within a single scenario. For example, variables related to animal growth and production, food intake, manure production and nutrient output are all related to each other, i.e. change in one variable will cause a change with a certain direction in another (Leinonen et al., 2012a, 2012b). The advantage of using mechanistic sub-models for animal and crop production, as was done in the present study, is that these relationships are automatically built in the results. During each Monte Carlo simulation, any random change in one input variable would cause a realistic response in others. This will prevent the overestimation of the total uncertainty, which would occur if the errors in each input would be considered to be completely independent from each other.

3.4. Other issues

The long-standing "battery" cage system used in egg production was banned in the EU from January 2012 (EU Council Directive 1999/74/EC). As a result, the proportion of free range egg production has strongly increased in the UK, and some producers have also started to use modern "enriched" cages, which are allowed by the EU. Detailed comparison between the free range and cage systems was not carried out in this study, because we did not have enough data on bird performance and energy use in enriched cage egg production. However, preliminary results suggest that similar performance can be expected in enriched cages as in conventional battery cages, a system described by Leinonen et al. (2012b). Furthermore, based on the data obtained from the egg production industry in the study of Leinonen et al. (2012b), it was concluded that layer diets are similar in both systems, and the same baseline soya-based diet could be applied to them. Therefore, it is reasonable to assume that the alternative diets used in the current study for the free range system would be also applicable for the enriched cage system. Furthermore, in the case of GWP, for example, the relative contribution of feed in the total impact of the whole production system was also very similar, i.e. 72% for cage and 70% for free range (Leinonen et al. 2012b). So, it can be expected that the relative effects of alternative diets found in this study will be similar to those in the new enriched cage system.

Possible effects of the alternative diets on animal performance or welfare were not taken into account in this study. It was assumed that when the nutrient composition of feed does not change, bird feed intake and performance will be unaffected (Emmans and Kyriazakis, 2001). However, although the levels of the main nutrients and energy were set to be equal in all diets, it is still possible that some of the alternative ingredients may have anti-nutritional or other properties, and affect the feed intake, growth rate, number of eggs produced, egg weight, quality of the manure, etc., as discussed in earlier studies by e.g. McNeill et al. (2004), Kluth et al. (2005) and Vilarino et al. (2009). Such anti-nutritional factors may include tannins in beans and trypsin inhibitors in peas. If such effects occur, they may also have downstream consequences on environmental impacts. For example, decreasing feed conversion efficiency would automatically increase the impacts per unit of the final product, if other factors remain unchanged. Although the nutrient content of the manure was taken into account in this study, further effects may arise from possible changes in manure moisture content, which may affect the NH_3 emissions (and at least secondary N_2O emissions) from housing (e.g. Groot Koerkamp et al., 1998). Experimental studies are required to quantify the possible effects of different diets on animal performance and manure quality, in order to make any recommendations on their use for the purpose of reducing environmental impacts. Such work would also enable economic comparisons to be made with confidence.

4. Conclusions

The results of this study show that there is limited potential to reduce GHG emissions of poultry production by replacing soya meal with alternative protein sources, and confirms the earlier observations by Baumgartner et al. (2008), who also found relative small changes in environmental impacts when reducing the use of soya in livestock feed. Replacement of soya also results in changes in the inclusion rates of other ingredients, which are needed to maintain the energy and nutrient content of the diets at required levels. In some cases, required inclusion of other ingredients may partly counteract the beneficial effect on GWP of removing soya. Such effects observed in this study clearly suggest that the diets must be considered as a whole, not just as replacement of one ingredient with another, when evaluating the environmental benefits of alternative protein sources. In a recent study, Dekker et al. (2013) used LCA to assess the potential to reduce the integral ecological impact of Dutch organic egg production by replacing currently used imported diet ingredients with Dutch diet ingredients. They also showed that not a single but simultaneous replacement of feed ingredients had the highest potential to reduce environmental impacts of feed production.

As this and other recent studies (e.g. Meul et al., 2012) demonstrate, the potential to reduce the GWP of livestock production by using alternative protein sources to soya in animal feed strongly depends on the method of accounting for GHG emissions arising from LUC. Beneficial effects of using the alternative protein sources to soya were seen only when indirect LUC-related emissions were excluded in the analysis. A consensus on the most equitable way of accounting for direct and indirect LUC emissions is, therefore, required.

Only minimal changes can be achieved in EP with the alternative protein sources. In the case of AP, significant reduction can be achieved if the crude protein content of the diets is reduced by using a combination of alternative protein crops and pure amino acids.

The results of this study also demonstrate the importance of the use of a systematic uncertainty analysis when the environmental impacts of different scenarios agricultural production are compared. This allows for quantitative comparisons based on statistical significance. A consequence of this is the need for identification of the different types of errors and their correlations within and between the scenarios in consideration.

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TABLES

Table 1. Inclusion rates of the main ingredients (%) in the diets used to estimate the environmental impact of broiler systems. The full ingredient and chemical composition of the diets is provided in the Supplementary Material.

	Wheat	Soya	Rapeseed	Beans	Peas	Sunflower meal	Vegetable oil	Amino Acids
Baseline (soya) diet								
- Starter Crumb	54.4	33.5	5.0	-	-	-	3.4	0.7
- Grower	60.2	25.5	7.5	-	-	-	3.6	0.7
- Finisher	66.0	18.0	10.0	-	-	-	3.2	0.7
- Withdrawal	67.6	17.0	10.0	-	-	-	2.8	0.7
Bean diet, realistic								
- Starter Crumb	54.4	28.5	5.0	5.0	-	-	3.2	1.0
- Grower	57.9	20.0	7.5	7.5	-	-	3.7	0.9
- Finisher	59.5	14.0	10.0	10.0	-	-	3.7	0.7
- Withdrawal	61.0	13.0	10.0	10.0	-	-	3.4	0.7
Bean diet, extreme								
- Starter Crumb	52.2	25.5	5.0	10.0	-	-	3.3	1.1
- Grower	54.1	16.0	7.5	15.0	-	-	3.9	1.0
- Finisher	54.0	9.0	10.0	20.0	-	-	4.0	0.9
- Withdrawal	56.1	7.5	10.0	20.0	-	-	3.6	0.9
Pea diet, realistic								
- Starter Crumb	52.1	28.0	5.0	-	7.5	-	3.4	1.0
- Grower	53.4	17.0	7.5	-	15.0	-	3.7	0.9
- Finisher	54.0	9.5	10.0	-	20.0	-	3.6	0.8
- Withdrawal	54.2	9.5	10.0	-	20.0	-	3.6	0.8
Pea diet, extreme								
- Starter Crumb	51.1	26.5	5.0	-	10.0	-	3.4	1.0
- Grower	51.0	14.5	7.5	-	20.0	-	3.5	1.0
- Finisher	48.0	5.0	10.0	-	30.0	-	3.8	0.9
- Withdrawal	48.5	5.0	10.0	-	30.0	-	3.7	0.9
Sunflower diet, realistic								
- Starter Crumb	55.0	30.0	5.0	-	-	2.5	3.7	0.9
- Grower	59.3	25.8	7.5	-	-	3.8	4.2	0.8
- Finisher	61.7	16.0	10.0	-	-	5.0	4.5	0.7
- Withdrawal	62.1	16.0	10.0	-	-	5.0	4.5	0.6
Sunflower diet, extreme								
- Starter Crumb	53.5	28.5	5.0	-	-	5.0	4.2	0.9

- Grower	57.2	19.5	7.5	-	-	7.5	5.0	0.9
- Finisher	58.5	13.0	10.0	-	-	10.0	5.7	0.8
- Withdrawal	58.3	13.5	10.0	-	-	10.0	5.7	0.7

Table 2. Inclusion rates of the main ingredients (%) in the diets used to estimate the environmental impact of egg production systems. The full ingredient and chemical composition of the diets is provided in the Supplementary Material.

	Wheat + Wheatfeed	Soya	Rapeseed	Beans	Peas	Sunflower meal	Vegetable oil	Amino Acids
Baseline (soya) diet								
- Starter Crumb	70.9	20.1	-	-	-	4.0	1.8	0.3
- Rearer	76.4	9.7	-	-	-	10.0	0.8	0.2
- Developer	79.7	6.7	-	-	-	10.0	0.5	0.2
- Early Lay	67.4	14.5	-	-	-	6.0	1.8	0.3
- Late Lay	68.5	12.0	-	-	-	7.0	1.6	0.3
Bean diet, realistic								
- Starter Crumb	67.3	16.0	-	7.5	-	4.0	1.8	0.4
- Rearer	71.2	4.5	-	10.0	-	10.0	1.0	0.4
- Developer	78.3	4.5	-	10.0	-	4.0	0.0	0.2
- Early Lay	62.1	9.5	-	10.0	-	6.0	1.9	0.4
- Late Lay	61.7	8.0	-	10.0	-	7.0	2.3	0.3
Bean diet, extreme								
- Starter Crumb	63.4	12.0	-	15.0	-	4.0	2.1	0.5
- Rearer	65.2	0.0	-	20.0	-	10.0	1.4	0.4
- Developer	72.4	0.0	-	20.0	-	4.0	0.3	0.3
- Early Lay	57.4	4.0	-	20.0	-	6.0	2.0	0.5
- Late Lay	56.9	2.5	-	20.0	-	7.0	2.4	0.5
Pea diet, realistic								
- Starter Crumb	66.3	17.0	-	-	7.5	4.0	1.9	0.4
- Rearer	70.9	5.0	-	-	10.0	10.0	0.8	0.4
- Developer	77.3	4.5	-	-	10.0	5.0	0.0	0.2
- Early Lay	61.2	10.5	-	-	10.0	6.0	1.9	0.4
- Late Lay	61.5	8.5	-	-	10.0	7.0	2.0	0.3
Pea diet, extreme								
- Starter Crumb	61.5	14.0	-	-	15.0	4.0	2.1	0.4
- Rearer	65.9	0.0	-	-	20.0	10.0	0.8	0.4
- Developer	71.7	0.0	-	-	20.0	5.0	0.0	0.3
- Early Lay	55.5	6.0	-	-	20.0	6.0	2.0	0.4
- Late Lay	54.6	5.0	-	-	20.0	7.0	2.4	0.3
Rapeseed diet, realistic								

- Starter Crumb	67.4	16.5	5.0	-	-	7.0	0.8	0.3
- Rearer	72.7	7.0	5.0	-	-	12.0	0.3	0.2
- Developer	75.5	4.0	5.0	-	-	12.5	0.0	0.2
- Early Lay	65.8	12.0	5.0	-	-	6.0	0.9	0.3
- Late Lay	66.1	10.0	5.0	-	-	8.0	0.0	0.3
Rapeseed diet, extreme								
- Starter Crumb	64.7	15.0	10.0	-	-	7.0	0.0	0.3
- Rearer	67.9	4.0	10.0	-	-	15.0	0.0	0.3
- Developer	70.9	0.0	10.0	-	-	16.0	0.0	0.2
- Early Lay	62.1	10.0	10.0	-	-	7.5	0.1	0.3
- Late Lay	65.0	6.0	10.0	-	-	8.0	0.0	0.4

Table 3. Global warming potential (GWP, kg CO_2 equivalent, 100 years timescale) per 1000 kg expected edible broiler carcass weight or 1000 kg eggs with of different diets and different scenarios for land use change (LUC). The coefficient of variation of GWP was 5-6 % with all diets and the GWP with any of the alternative diets was not significantly different (P<0.05) from the GWP with the soya diet in any LUC scenario (For details of the scenarios see Methods).

Scenario	Baseline (Soya)	Bean		Pea		Sunflower		Rapeseed	
		Realistic	Extreme	Realistic	Extreme	Realistic	Extreme	Realistic	Extreme
Broiler, "Best estimate"	4355	4191	3998	4019	3847	4387	4394	-	-
Broiler, "Sustainable soya"	3581	3579	3565	3537	3501	3695	3797	-	-
Broiler, "Top-down"	4140	4125	4102	4088	4058	4168	4194	-	-
Egg, "Best estimate"	3393	3252	3032	3248	3085	-	-	3257	3143
Egg, "Sustainable soya"	2946	2959	2934	2948	2913	-	-	2891	2900
Egg, "Top-down"	3423	3418	3389	3409	3387	-	-	3457	3462

Table 4. Eutrophication potential (EP, kg PO_4 equivalent) per 1000 kg expected edible broiler carcass weight or 1000 kg eggs with different diets. The coefficient of variation of EP was 5-6 % with all diets and the EP with any of the alternative diets was not significantly different (P<0.05) from the EP with the soya diet.

System	Baseline (Soya)	Bean		Pea		Sunflower		Rapeseed	
		Realistic	Extreme	Realistic	Extreme	Realistic	Extreme	Realistic	Extreme
Broiler	20.55	20.30	20.14	20.09	19.88	20.51	20.83	-	-
Egg	22.69	23.01	22.96	22.97	23.24	-	-	23.02	23.19

Table 5. Acidification potential (AP, kg SO_2 equivalent) per 1000 kg expected edible broiler carcass weight or 1000 kg eggs with different diets. The coefficient of variation of AP was 4-7 % with all diets.

System	Baseline (Soya)	Bean		Pea		Sunflower		Rapeseed	
		Realistic	Extreme	Realistic	Extreme	Realistic	Extreme	Realistic	Extreme
Broiler	47.14	42.94	40.05	40.29	37.28*	45.31	45.27	-	-
Egg	66.95	64.81	61.33	65.08	63.06	-	-	67.27	66.31

* indicates statistically significant difference (P<0.05) when compared to the soya diet

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