Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: Egg production systems

I. Leinonen,*[1] A. G. Williams,† J. Wiseman,‡ J. Guy,* and I. Kyriazakis*

*School of Agriculture, Food, and Rural Development, Newcastle University, Newcastle upon Tyne, NE1 7RU United Kingdom; †School of Applied Sciences, Cranfield University, Bedford, MK43 0AL United Kingdom; and ‡School of Biosciences, University of Nottingham, Sutton Bonington Campus, LE12 5RD United Kingdom

ABSTRACT The aim of this study was to apply a life cycle assessment (LCA) method, from cradle to gate, to quantify the environmental burdens per 1,000 kg of eggs produced in the 4 major hen-egg production systems in the United Kingdom: 1) cage, 2) barn, 3) free range, and 4) organic. The analysis was based on an approach that applied a structural model for the industry and mechanistic submodels for animal performance, crop production, and nutrient flows. Baseline feeds representative of those used by the UK egg production industry were used. Typical figures from the UK egg production industry, feed intake, mortality of birds, farm energy, and material use in different systems were applied. Monte Carlo simulations were used to quantify the uncertainties in the outputs and allow for comparisons between the systems. The number of birds required to produce 1,000 kg of eggs was highest in the organic and lowest in the cage system; similarly, the amount of feed consumed per bird was highest in the organic and lowest in the cage system. These general differences in productivity largely affected the differences in the environmental impacts between the systems. Feed production, processing, and transport caused greater impacts compared with those from any other component of production; that is, 54 to 75% of the primary energy use and 64 to 72% of the global warming potential of the systems. Electricity (used mainly for ventilation, automatic feeding, and lighting) had the second greatest impact in primary energy use (16–38%). Gas and oil (used mainly for heating in pullet rearing and incineration of dead layer birds) used 7 to 14% of the total primary energy. Manure had the greatest impact on the acidification and eutrophication potentials of the systems because of ammonia emissions that contributed to both of these potentials and nitrate leaching that only affected eutrophication potential. The LCA method allows for comparisons between systems and for the identification of hotspots of environmental impacts that could be subject to mitigation.

Key words: environmental impact, egg production, energy use, carbon footprint

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INTRODUCTION

Egg production has been identified as being relatively environmentally efficient (per unit weight) compared with the efficiency of the production of other animal commodities (Williams et al., 2006). However, like all agricultural systems, any current poultry system has the scope to be improved, and thus, has the potential to reduce its environmental impacts. With an annual production of 8,862 million eggs (about 0.4 billion kg) produced in the United Kingdom (Defra, 2009) and 61 billion kg produced annually worldwide (FAO, 2011), egg-laying systems have the potential to be significant contributors to both resource use and environmental burdens. In the current paper, the environmental impacts of different egg production systems in the UK are considered; the aim of the study was to identify opportunities for reducing these impacts within each system.

In a previous paper (Leinonen et al., 2012) where the environmental impacts of broiler production systems were investigated, the analysis was undertaken by applying a cradle-to-gate approach to the life-cycle assessment (**LCA**) method. In that paper, the advantages of applying the LCA methodology were demonstrated, including the fact that the LCA is more holistic than most other methods used to quantify the environmental impacts of commodities. The LCA method includes several other impact categories in addition to global warming potential (**GWP**), which is generally the only

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[1]Corresponding author: ilkka.leinonen@newcastle.ac.uk

impact considered in carbon footprinting, for example. Consideration of other environmental impact dimensions, such as eutrophication potential (**EP**) or acidification potential (**AP**) is of concern in agricultural systems (Sutton et al., 2011). In the current paper, the objective was to quantify the environmental impact of the 4 main UK egg production systems: 1) conventional cage, 2) barn, 3) free range, and 4) organic laying through the LCA method.

Currently, laying cages are the most common method of commercial egg production in the UK, representing around 55% of the eggs produced in 2010 (Defra, 2009). However, by January 1, 2012, battery cages will be banned across the European Union and all British egg producers must be compliant with that ban. Although the conventional battery cages might be partly replaced by larger enriched (or colony) cages, the expectation is that the prevalence of alternative systems will increase in the UK and across the European Union after 2012. These systems, which include barn, nonorganic free range, and organic free range, currently represent 4, 37, and 4% of the total UK egg production, respectively (Defra, 2009). All of these systems have major differences in their husbandry, and therefore, they might be expected to lead to different environmental impacts. It is then possible that they would offer different opportunities for reducing these impacts within each system.

MATERIALS AND METHODS

LCA General Principles

The LCA method evaluates production systems logically to account for all inputs and outputs that cross a specified system boundary and it relates these to useful outputs. The useful output is termed the functional unit that must be of a defined quantity and quality; for example, 1,000 kg of bread-making quality wheat. The principles and guidelines are established in the international standards (ISO 14040-14048, BSI, 2006). There are 4 phases in an LCA study:

1) Goal and scope definition: defining the purpose and limits of the study.
2) Inventory analysis: compiling an inventory of relevant inputs and outputs of a system.
3) Impact assessment: evaluating the potential environmental impacts associated with those inputs and outputs.
4) Interpretation phase: interpreting the results of the inventory and impact phases in relation to the objectives of the study, assessing data quality, sensitivity analysis, uncertainty analysis, and so on, and reporting the results.

Goal and Scope

The aim of the current study was to apply the LCA method from cradle to gate in order to quantify the environmental burdens of 4 main chicken egg production systems in the UK (cage, barn, free range, and organic), and hence, to identify the main opportunities for reducing these environmental impacts within each system. The intended audiences were the egg producers, the agri-environmental scientific community, and other stakeholders in the supply and consumption chain. The functional unit was 1,000 kg of marketable eggs at the farm gate. All upstream inputs were included in the analysis (Figure 1).

Economic allocation was used to partition the burdens between coproducts (e.g., human food and animal feed) in feed crop production, and between eggs and spent laying hens in egg production (i.e., value of layer meat produced per 1,000 kg of eggs/value of 1,000 kg of eggs). The principles for quantifying the resource use, burdens, and environmental impacts followed those presented in Leinonen et al. (2012). Details of the impact categories applied in this study are given in Appendix 1 in Leinonen et al. (2012).

Systems Approach

Audsley et al. (1997) conducted a study to harmonize the application of LCA in agriculture; the current study followed the principles therein. The general approach in the current study has been outlined in the companion paper (Leinonen et al., 2012), which followed the approach of Williams et al. (2006). This included structural models of the industry, process models, and simulation models that were unified in a systems approach, so that changes in one area caused consistent interactions elsewhere. This approach was applied to both feed crop and animal production. Empirical data were used where no functional relationships were available. The systems modeled included crop production, noncrop nutrient production, feed processing, breeding (including maintaining breeding flocks, hatching, and pullet rearing, both for breeders and layers), production (including performance of pullets and layers), energy and water use in housing, manure management, and general waste management

Capital goods, such as tractors, ploughs, and harvesters, were included in all agricultural activities, which dominate the direct energy use terms in crop production and have a smaller influence in animal production. Terms for capital were not included in the inventory data for energy intensive processes, such as N fertilizer or energy carrier production and delivery. The inclusion of capital goods in the latter has a trivial effect, whereas direct energy use in crop production (as diesel) is increased by about 30 to 40% through the inclusion of capital goods.

The main differences between the current study and that of Williams et al. (2006) were that noncrop feeds, such as pure amino acids, were included in our analysis, and particularly, the bird performance (growth, egg production, and nutrient excretion) was modeled mechanistically (see Animal Growth and Production

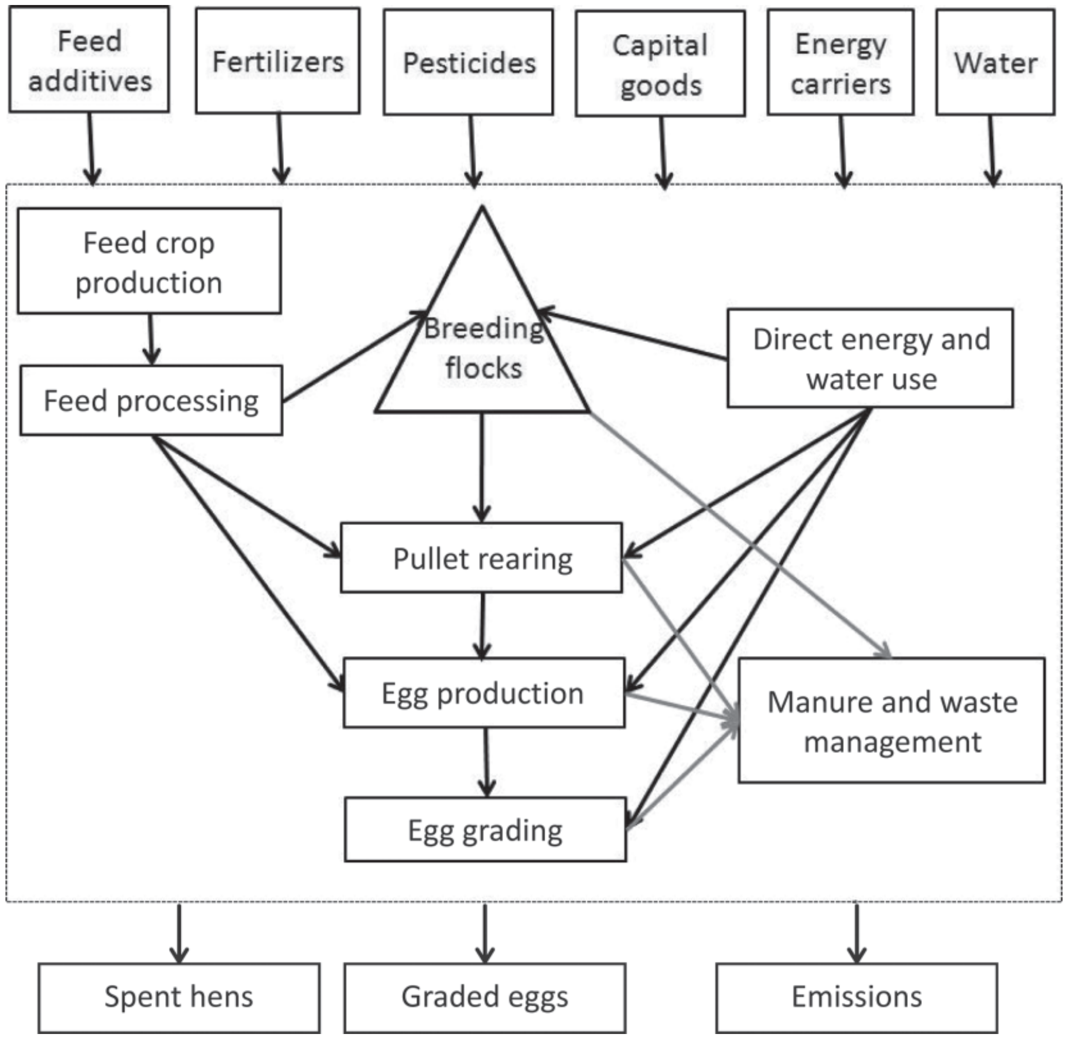

Figure 1. The structure, boundaries, and main contents of the egg production systems considered.

Submodel section below). In addition, some new crop life-cycle inventory (**LCI**) data were also included, such as palm oil and sunflower meal, and the impact of land-use changes in the production of some crops were also taken into account (see Crop and Manure Submodel section below). The sources of data on energy carriers were updated to use those from the European reference life-cycle database, and some detailed processes were revisited. The emission factors for greenhouse gases (**GHG**) and the GWP were also based on those used in the IPCC (2006) guide to national inventory compilations. The GWP of 1 kg of methane and 1 kg of nitrous oxide are equivalent to 25 and 298 kg of CO_2 on a 100-yr time scale (**CO_2e**), respectively.

Egg Production Structural Model

The structural model calculated all of the inputs required to produce the functional unit, allowing for breeding overheads (3 generations of breeding stock), mortalities, and productivity levels. It also calculated the outputs, both useful (eggs and spent hens) and unwanted. Changes in the proportion of any activity had to result in changes to the proportions of other variables to keep producing the desired amount of output. Establishing how much of each activity (i.e., subsystem, for example, pullet rearing) was required was found by linear equations that describe the relationships that link the activities together.

The functional unit used in the current study was 1,000 kg of eggs, but this may be met by different numbers of eggs. Based on the data from the UK egg production industry, the egg weights were 62 and 63.5 g for cage and alternative systems, respectively, hence requiring 16,129 and 15,748 eggs, respectively.

The general structure of the model was based on multiple linear equations, which were solved simultaneously with a code written in Visual Basic for applications specifically for this purpose. The solution was the amount, X (for example, the number of birds), of each activity i (e.g., laying or breeder system), that produced the desired amount of output Z (e.g., the amount of eggs or meat),

$$Z = \sum_{i=1}^{n} z_i X_i, \quad [1]$$

where z_i is the output of activity i and also satisfies the set of flows between activities:

$$\sum_{i=1}^{n} c_{ij} X_i = 0, j = 1...p, \qquad [2]$$

where c_{ij} is the supply or demand of j by activity i. Demands are negative and supplies are positive, and total supply must equal total demand. For example, the supply of pullets from a pullet rearing system must equal the demand of birds in the laying system (and allow for mortalities).

The total amount M of material k flowing into the system was

$$M_k = \sum_{i=1}^{n} m_{ik} X_i, k = 1...q, \qquad [3]$$

where m_{ik} is the flow of material k into activity i.

The LCI for the system was the total B of each burden l,

$$B_l = \sum_{k=1}^{p} M_k b_{kl}, l = 1...r, \qquad [4]$$

where b_{kl} is the amount of burden l produced by the use or disposal of material k, and M_k is the total amount of material.

The LCI identifies the contribution of each material,

$$B_{kl} = M_k b_{kl}, \qquad [5]$$

or activity,

$$B_{il} = X_i \sum_{k=1}^{q} m_{ik} b_{kl}. \qquad [6]$$

These equations provided information to enable particular hotspots to be identified. The structure of the model was such that changes could be made whether a parameter value was derived empirically or was linked to another model, but the linked model approach was used whenever possible. The main additional feature of this study was the connection to a mechanistic submodel that linked bird growth, egg production, feed intake, and excreta composition. This allowed variations in production methods to be analyzed when no empirical data were available. These could include variations in the length of the production cycle, feed composition, or bird maintenance energy requirement in different environmental conditions.

Animal Growth and Production Submodel

A mechanistic animal growth and production model was used in the current study for 3 purposes: 1) to calculate the total consumption of each feed ingredient during the whole production cycle; 2) to calculate the amounts of main nutrients, N, P, and K, in manure produced by the birds during the production cycle; and 3) to include the correlation between changes in the production figures (egg production, feed intake, and nutrient output) to be applied in the uncertainty analysis (see below). The model was based on the principles presented by Emmans and Kyriazakis (2001) and Wellock et al. (2003), and predicted the daily feed intake, which varies considerably during the bird life cycle, of a single bird as a function of feed composition and energy and protein requirements of the bird. This included requirements for both production (body growth and eggs) and maintenance. The daily egg production was an input of the mechanistic model and was based on the age-dependent target values from the breed manuals. Given that the actual egg production varied between the systems, the daily target figures were scaled using a constant multiplier over the whole laying period to produce the actual amount of eggs per layer (including the estimated number of the uncollected eggs) typical for each of the production systems (Table 1).

The daily feed intake was assumed to equal the minimum amount of feed to fulfill both the energy and protein requirements of the animal (Emmans and Kyriazakis, 2001; Wellock et al., 2003). The protein requirement for birds was determined by the first limiting amino acid in the feed. The energy requirement of maintenance, and therefore also the feed conversion ratio (**FCR**), varies between the production systems as a result of differences in bird activity and environmental conditions, such as temperature; therefore, the model had to be calibrated for its application in actual production systems. The calibration ensured that the modeled total feed intake in each system was equal to the actual feed intake based on the data provided by the industry. The model calibration was done by using the principle of energy balance to calculate the feed consumption needed to produce a certain amount of eggs. The energy in consumed feed was allocated to body growth, egg production (including uncollected eggs), excreta, and spillage, on the basis of estimates obtained from the UK egg production industry and from literature. The energy obtained from the feed and not included in any of these components had to be allocated to maintenance; therefore, the maintenance function in the model was adjusted to match the level of feed intake obtained from the industry data. It also took into account the additional food intake from foraging in free-range and organic systems. According to the output of the model calibration, considerable differences in maintenance occurred between the systems; this is consistent with literature as reviewed by Sakomura, (2004). These differences are caused by both the impacts of different levels of bird physical activity and differences in bird heat loss due to different environmental conditions and resulted in higher feed intake in alternative systems compared with that in the cage system, as indicated in the industry data shown below.

Table 1. Typical production and food intake figures for the different egg production systems in the United Kingdom as provided by the UK industry and applied in this study

Variable	Cage	Barn	Free range	Organic
Laying period, wk	56	56	56	56
Eggs collected/hen[1]	315	300	293	280
Average egg weight, g	62	63.5	63.5	63.5
Uncollected eggs, %	0	1.5	1.5	1.5
Feed consumption,[2] g/bird per day	115	125	130	131
Mortality, %	3.5	6	7	8
Food spillage, %	1	3	3	3
Indoor stocking density, birds/m^2 (floor area)	52	11.7	6	6
Outdoor stocking density, birds/ha	n/a[3]	n/a	1,000	500
Average number of birds/house	121,600	16,000	4,360	1,750
Type of bedding	n/a	wood shaving	wood shaving	straw
Amount of bedding, kg/bird	n/a	0.5	1	1.5
Down time between cycles, wk	2	3	3	3[4]

[1]Based on the initial number of hens.

[2]Includes spillage, excludes possible foraging.

[3]n/a = not applicable.

[4]Houses were rotated between 2 ranging areas with a full cycle in each.

Based on these daily values calculated by the model, the total consumption of each type of feed during the production cycle was quantified, and finally, the environmental burdens of the feeds were calculated on the basis of total consumption of each feed ingredient. For ingredients produced from arable crops (a major part of the diets), the environmental burdens were quantified using separate submodels for crop productions (see Crop and Manure Submodel section below).

The model calculated the N, P, and K contents of the manure according to the mass balance principle; that is, 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 addition to the nutrients excreted by the birds, nutrients in the spilled feed and uncollected eggs were added to the manure in the calculations. This output was then used to calculate the emissions to water and atmosphere (burdens) and replacement of fertilizers in crop production (a credit) as described below. However, for nonorganic free-range birds, the proportion of nutrients excreted outside the house were not credited to crop production because the entire ranging area was grassland, and according to the information provided by the UK egg production industry, was not used for growing commercial crops (unlike in the organic system), and therefore, no fertilizers would be applied in such an area.

The primary output of the mechanistic production model was the feed intake and manure production of one typical bird at any stage of the production cycle. However, mortalities with consequent lost egg production and reduced feed consumption were also taken into account. These were calculated on the basis of typical mortality rates for each production system and assuming a uniform mortality and feed consumption during the laying cycle. Hence, the feed consumed by 1 layer with a full lifespan or 2 layers with half life spans differed by the feed needed to raise 1 pullet (all other burdens are scaled pro rata).

Crop and Manure Submodel

A separate submodel 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 modeled. Some of the crops were partly or wholly produced overseas, including maize, soy, sunflower, palm oil, and organic wheat. In these cases, production was modeled as closely as possible using local techniques, and transport burdens for importing were also included.

The GHG emissions from land-use changes were included in the analysis in the case of crops where recent conversion of natural vegetation to agricultural land has occurred as a result of their cultivation (soy and palm oil). The proportions of nonorganic crops from mature ($\geq$20 yr from the time of any conversion; BSI, 2008) and new agricultural land were specific for each country of origin, but all organic crops were assumed to have originated from mature agricultural land. Nonorganic soy was imported mainly from Brazil and Argentina, in which land may have been converted from forest, cerrado, managed pasture, or arable land used for other crops. For this crop, a weighted average of origin was calculated based on the land-use change statistics of the UN Food and Agricultural Organization (FAO, 2011). These were used to estimate the rate of conversion of land from forest and pasture and the land-use change emissions were discounted over 20 yr using the time scale in BSI (2008) to obtain a weighted average value for contemporary soy production (Audsley et al., 2010).

Poultry manure is the source of direct gaseous emissions of ammonia (NH_3), nitrous oxide (N_2O), and to a lesser extent methane (CH_4) that occur during housing, storage, and land spreading. Manure management also uses energy, and these burdens are debited against the poultry along with burdens from other sources. The interactions between manures, soils, and crops are complex, but in the long term, all of the nutrients that were 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 fertilizer to winter wheat as described by Sandars et al. (2003) and implemented by Williams et al. (2006). For organic systems, the supply of N from a dedicated, uncropped legume was used instead of synthetic N fertilizer (ammonium nitrate), with rock P and K used instead of triple superphosphate and potassium chloride.

Production Systems and Sources of Data

The production systems considered in this study included 4 laying systems (cage, barn, free range, and organic), pullet rearing, and breeding. The pullets were produced using either cage rearing or floor rearing. For this study, it was assumed that 50% of the birds used in cage laying came from cage rearing and 50% from floor rearing; for all other systems, all birds came from floor rearing. The pullet rearing for organic birds was similar to nonorganic floor rearing with the exception of the feed composition (see below). In all systems, the rearing period lasted 16 wk and the laying period 56 wk, as is the common practice. The breeder system was identical in the case of all laying systems and all generations of breeder birds.

The bird genotype used for all production systems in the current study was Hy-Line Brown, which is widely used by the UK egg production industry, including the alternative laying systems. According to the breed manual, these birds have a body mass of 1.4 kg at the age of 17 wk and 1.98 kg at the age of 70 wk (Hy-Line, 2009). The feed intake and egg production vary depending on the production system and, for these figures, the estimates provided by the industry were used (Table 1).

Simplified baseline feeds representative of those used in the UK were constructed using information provided by the industry. Similar feeds were applied for cage, barn, and free-range birds, and they were changed 5 times during the bird life cycle (starter, rearer, developer, early lay, and late lay), according to common practice. The feeds for the organic birds were changed 4 times (grower, rearer, early lay, and late lay). The details of the feeds are presented in the Appendix in Tables A1, A2, A3, A4, and A5.

The general data on the industry structure were obtained from typical production units representing each activity considered in the study, including breeding, floor rearing, cage rearing, cage laying, barn laying, free-range laying, and organic laying. These data for different laying systems are given in Table 1. The actual energy consumption for heating, lighting, ventilation, and feeding was based on average data from typical farms (generally 3 farms/activity and system), as provided by the industry. Information about the type and amount of bedding was also obtained from the industry. For the purpose of this study, it was assumed that all pullet, layer, and breeder manure was transported for soil improvement, excluding the proportion that was excreted outside (assumed to be 10% in the free-range laying system and 20% in the organic laying system). In the organic laying system, the houses were rotated between 2 ranging areas; 1 of them was used for the whole production cycle, whereas the other remained free of birds during that period (typically a year). It was assumed that organic winter wheat was grown in between bird production cycles to quantify the value of nutrients from excreta. It should be noted that different organic standards can apply and the basic EU regulation requires the land to be rested for at least 2 mo, but the Soil Association in the UK requires at least 9 mo rest from birds and that the nutrients from excreta are used (Soil Association, 2009). The latter was modeled because the particular unit that generated the data was Soil Association accredited.

Emissions of NH_3, N_2O, and CH_4 from excreta were calculated following the methods of Williams et al. (2006), which are based on the UK national inventories (Chadwick et al., 1999; IPCC, 2006; Misselbrook et al., 2008; Sneddon et al., 2008), emission factors, and methods. Additional data, such as LCI of agricultural buildings and machinery, came from Williams et al. (2006).

Uncertainty

Uncertainties (for example, potential measurement errors, variation in activity, and production data) and the impact of these on the model output were quantified to make it possible to evaluate differences between the systems under consideration. This was done according to Leinonen et al. (2012) with the Monte Carlo approach. The LCA model, together with the animal production submodel, was run 5,000 times, and during each run, a value of each input variable was randomly selected from a predetermined distribution for this variable. The final model output was the mean values and the SD of the key categories of the environmental impacts (primary energy use, GWP, AP, and EP). In addition, the mean values of some other impact categories (land occupation, abiotic resource use, and pesticide use) are presented, but these categories were not included in the uncertainty analysis because sufficient data on their variations were not available.

The range of variation between farms (maxima and minima) in the production and energy use data was obtained from the industry. The information on variation in energy use, including electricity and liquid propane gas, was applied to specify random distributions that were directly used in the Monte Carlo simulations. The variation in the animal production variables was more complex because these variables were connected to each other. For example, higher egg production caused a higher energy requirement, which had affected feed intake, and then higher feed intake caused a larger amount of excreted nutrients. The correlations between

Table 2. Uncertainties (CV) and their distributions of the main variables of the life cycle assessment model

Variable	CV A[1], %	CV total (A[1]+B[2]), %	Distribution
Number of eggs/bird	2 to 5	2 to 5	Triangular
Egg weight	1	1	Triangular
Pullet feed intake	1	1	Normal
Layer feed intake	1 to 2	1 to 2	Normal
Amount of N in manure	1 to 2	1 to 3	Normal
Amount of P in manure	1 to 2	2	Normal
Amount of K in manure	1 to 2	1 to 2	Normal
Laying farm electricity consumption/bird	5 to 9	5 to 9	Triangular
Laying farm liquid propane gas consumption/bird	71 to 73	71 to 73	Triangular
Laying farm oil consumption/bird	47 to 56	47 to 56	Triangular
Rearing farm electricity consumption/bird	n/a	7 to 27	Triangular
Rearing farm liquid propane gas consumption/bird	n/a	18 to 104	Triangular
Rearing farm oil consumption/bird	n/a	25 to 87	Triangular
Layer mortality	17 to 40	17 to 40	Triangular
Feed spillage	5	5	Normal
Environmental impacts/1,000 kg of feed	2 to 5	3 to 13	Normal
N_2O emission factor	n/a	30	Lognormal
NH_3 emission factor	n/a	36	Lognormal
CH_4 emission factor	n/a	29	Lognormal
Transport distance	n/a	3	Normal
Proportion of ammoniacal nitrogen in excreta	n/a	2 to 3	Normal
Denitrification factor	n/a	5	Normal
Feed spillage	5	5	Normal

[1]A uncertainties were considered to vary between systems.

[2]B uncertainties were considered to be similar between the systems.

these figures were built in the mechanistic animal production submodel, and therefore, were automatically taken into account in the uncertainty results. Variation in egg weight is also related to the number of eggs produced, and this relationship was also included in the analysis. Additional random variation was also included in the model parameters describing maintenance energy requirement, and the magnitude of this variation was adjusted to match the overall variation in the industry feed intake data. Variation in feed intake also affected the variation in the amount of excreted nutrients, and additional variation in the nutrient content of manure was induced by including a random variation in the nutrient content of the animal body and eggs.

The distributions of the direct GHG emission factors were based on IPCC (2006) guidelines, except ammonia was based on the UK NH_3 inventory (Misselbrook et al., 2008). The uncertainties in the environmental impact of the feed ingredients were a direct output of the crop production submodel.

The uncertainties in the input variables were divided into 2 groups: alpha (**A**) and beta (**B**) errors (Wiltshire et al., 2009). The A errors were considered to vary between systems, and therefore, were taken into account in statistical analyses of the differences between the systems. These errors included variation between farms in production, feed intake, and energy use figures. In contrast, B errors were considered to be similar between the systems but were needed for calculating the absolute uncertainty of the overall environmental impacts and for comparison with other studies. The CV for main input variables is shown in Table 2. The CV is presented separately for A errors only and for both A and B errors.

The statistical analysis to evaluate the differences between the systems was based on the overall A uncertainties of each impact category. For each system, a test variable z was calculated (Wiltshire et al., 2009):

$$z = \frac{|m_1 - m_2|}{\sqrt{CV_1^2 \times m_1^2 + CV_2^2 \times m_2^2}}, \quad [7]$$

where m_1 and m_2 are the mean values and CV_1 and CV_2 are the coefficients of variation of the 2 systems. If the value of z is greater than $z_{\alpha/2}$, then the 2 means are significantly different at the (1-α) confidence level. The probability level under consideration was α; it was 5% in this study. The $\alpha/2$ is used because this is a 2-sided test, given that the alternative hypothesis to equal means is nonequal means, not m_1 less than m_2 or m_1 greater than m_2.

Breakdown of Environmental Impacts

The results were broken down by material and energy flow and activity to demonstrate the reasons for the differences in environmental impacts between the systems.

The material and energy flow groups were feed and water (including production of crops and additives, feed processing, and transport of ingredients); electricity (consumed at the farms and hatcheries, not including feed production, processing, and transport of ingredients); gas and oil (consumed at the farms and hatcheries, not including feed production, processing, and transport of ingredients); housing and land (in-

Table 3. The mean values of the activity figures per 1,000 kg of eggs for the 4 production systems as calculated by the life cycle assessment model

Variable	Cage	Barn	Free range	Organic
Layer number	51.2	52.6	53.8	56.3
Number of eggs	16,129	15,748	15,748	15,748
Feed consumed,[1] kg	2,559	2,737	2,912	3,095
Water used,[1,2] m^3	5.11	5.23	5.35	5.60

[1]Includes breeders, pullets, and layers.

[2]Drinking and cleaning water, not virtual water from crop production.

cluding direct emissions of NH_3, CH_4, and N_2O from housing, burdens from construction of farm buildings and vehicles, and the ranging area in the free-range and organic systems, not including buildings and vehicles used in feed production, processing, and transport of ingredients); and manure and bedding (not including direct emissions of NH_3, CH_4, and N_2O from housing).

The activity groups were breeding (all breeding activity in the pyramid above the pullets of the commercial layer generation), pullet rearing, and commercial laying.

RESULTS AND DISCUSSION

The production of 1,000 kg of eggs required 51.2 laying birds in the cage system, 52.6 birds in the barn system, 53.8 birds in the free-range system, and 56.3 birds in the organic system (Table 3). This general trend in productivity also affected other aspects of derived activity data, such as feed consumption. Much of the explanation of the trends in environmental burdens that followed resulted from these variations in productivity and use of materials, particularly feeds.

In addition to the different amounts of feed consumption, the composition of feeds also varied between organic and nonorganic systems, resulting in different environmental burdens per equal amount of feed (Table 4). To demonstrate the relative importance of single feed ingredients, the breakdown of burdens (GWP is presented here as an example) for the feed used for the last phase of laying is shown in Table 5. The results show that feed wheat and soy meal had the highest proportion of GWP of the feed components in all of the systems. The high GWP of soy in nonorganic feed is largely caused by GHG released as a result of land-use changes (Leinonen et al., 2012). Other feed components varied between systems; for example, vegetable oil blend and pure amino acids had relatively large impacts in the nonorganic systems. The GWP of vegetable oil was dominated by the inclusion of palm oil and the land-use changes related to its production.

The main burdens from each whole system are listed in Tables 6, 7, 8, 9, and 10. The results show that the cage system had lower EP and AP than those of any other system ($P < 0.05$), and lower primary energy use and GWP compared with those of most of the alternative systems. The organic system had the highest values ($P < 0.05$) in the categories of primary energy use, EP, and AP. Much of these trends resulted from the overall feed efficiency. In the case of GWP, there were no statistically significant differences ($P > 0.05$) between the 3 alternative systems (barn, free range, and organic). In general, there were no significant differences between the barn and free-range systems, except for in their primary energy use where the barn system has the highest value. The pesticide use was lowest in the organic system being only about 3.5% of the amount in the nonorganic free-range system. The pesticides in the organic system originated from the use of a small amount of nonorganic ingredients (prairie meal and potato protein) and from the feed for breeder birds. In the near future, it is expected that nonorganic ingredients will not be allowed in organic production.

When comparing the material and energy flow groups (Table 6 to Table 10), feed caused higher overall environmental impacts than any other materials involved in production; for example, 54 to 75% of the primary energy use and 64 to 72% of the GWP of the system. Water contributed only about 0.25% to the feed and water group. In general, the environmental burdens originating from the feed were highest in the organic system, and this was also a major cause of the overall differ-

Table 4. Main burdens per 1,000 kg of concentrated feed (the values include burdens associated with feed processing)

Burden[1]	Layer, nonorganic	Layer, organic	Pullet, nonorganic	Pullet, organic
Primary energy used, GJ	4.30	6.23	4.41	7.03
GWP_{100}, 1,000 kg of CO_2e	0.785	0.749	0.768	0.862
EP, kg of PO_4 equivalent	2.97	6.92	3.08	8.07
AP, kg of SO_2 equivalent	3.10	2.99	3.23	3.48
Pesticide use, dose-ha	0.812	0.019	0.814	0.023
Abiotic resource use, antimony equivalent, kg	2.18	2.89	2.24	3.25
Land occupation, ha	0.155	0.500	0.156	0.582

[1]GWP_{100} = global warming potential over a 100-yr time period; EP = eutrophication potential; and AP = acidification potential.

Table 5. Proportions of global warming potential (GWP_{100}) of main components of organic and nonorganic layer feeds (for the last phase of laying)

Nonorganic	%	Organic	%
Wheat	41.9	Wheat	55.8
Soy meal	34.1	Soy meal	12.4
Vegetable oil blend	8.0	Processing[1]	8.4
Sunflower meal	6.9	Maize	8.1
Processing[1]	5.4	Sunflower expeller	5.7
Lysine	1.3	Wheat feed	3.3
Limestone	0.9	Prairie meal	1.4
Methionine	0.8	Potato meal	1.3
Mono-dicalcium phosphate	0.5	Mono-calcium phosphate	1.3
Phytase	0.1	Limestone	0.9

[1]Processing of mixtures; does not include processing of single ingredients.

ences between the organic and the other systems. There were 2 reasons for the high feed burdens in the organic system. First, the feed intake per bird was highest in the organic system, but the marketable egg production rate was lowest (Table 1, 3) As a result, the overall FCR (including pullet and breeder feed) was higher at 3,100 kg of feed/1,000 kg of eggs in the organic system compared with 2,560 kg of feed/1,000 kg of eggs in the cage system; the other systems were in between. Second, the environmental burdens originating from feed production were higher in the case of organic feed compared with the feed used for the other systems. For example, the primary energy needed to produce and transport 1,000 kg of organic layer feed applied in the current study was 6.23 GJ, whereas it was 4.30 GJ for the nonorganic system's feed (Table 4). This difference was partly caused by the fact that, according to the industry data, a larger proportion of organic ingredients was produced overseas compared with that of the standard feed and also by the generally smaller yields of organic crops (Williams et al., 2010). The EP from feed production was especially high in the organic system. This was caused by a higher leaching of nutrients in organic crop production. Although leaching per land area could be lower than that in nonorganic production, a lower yield and a higher land-use requirement resulted in a higher overall EP for organic crops. On the other hand, the GWP was lower in organic compared with in nonorganic feed. This was partly a result of GHG emissions from land-use changes related to the production of soy and palm oil in nonorganic feed.

Electricity (used mainly for ventilation, automatic feeding, and lighting) had the second largest impact on primary energy use (16–38%). The electricity use per 1,000 kg of eggs was of similar magnitude in the cage, free-range, and organic systems. Although the electricity requirement per unit area was higher in the cage system, it was magnified per bird place in free-range and organic systems because of the lower stocking density. Gas and oil (used mainly for heating in the pullet systems and incineration of dead birds in the layer systems) also incurred a relatively large proportion of primary energy use (8–14%).

Manure had the largest impact in the categories of AP and EP. This was mainly a result of ammonia emissions, which contributed to both potentials, together with nitrate leaching after land application, which only affected EP. The AP of manure was especially high in the organic system because the manure production of the organic birds per 1,000 kg of eggs was high (due to high feed intake and low productivity) and also the nitrogen content of the feed and manure was higher than that in the other systems. In some of the categories, including primary energy use, manure had a negative value; that is, it was a credit instead of burden. This was because of the use of manure as a fertilizer, which

Table 6. Primary energy use (GJ) for the 4 different systems considered per 1,000 kg of eggs[1]

Material or activity	Cage	Barn	Free range	Organic
Feed + water	11.56	12.09	12.85	19.89
Electricity	4.20	8.37	3.57	4.12
Gas + oil	1.26	1.97	2.55	2.47
Housing + land	0.25	0.19	0.26	0.32
Manure + bedding	−0.39	−0.42	−0.45	−0.38
Breeder	0.27	0.19	0.19	0.20
Pullet	3.23	3.87	3.97	5.10
Layer	13.38	18.14	14.62	21.12
Total	16.88[c] (1.01)	22.20[b] (1.20)	18.78[c] (1.15)	26.41[a] (1.62)

[a–c]Different superscripts indicate statistical difference ($P < 0.05$) between systems as based only on A uncertainties, which were considered to vary between systems.

[1]The SD (in parentheses) were based on A and B uncertainties. The B uncertainties were considered to be similar between the systems.

Table 7. Global warming potential (1,000 kg of CO_2, 100-yr timescale) for the 4 different systems considered per 1,000 kg of eggs[1]

Material or activity	Cage	Barn	Free range	Organic
Feed + water	2.10	2.22	2.36	2.41
Electricity	0.24	0.48	0.20	0.24
Gas + oil	0.09	0.14	0.18	0.18
Housing + land	0.38	0.48	0.50	0.54
Manure + bedding	0.11	0.13	0.14	0.06
Breeder	0.05	0.04	0.03	0.04
Pullet	0.51	0.55	0.57	0.60
Layer	2.36	2.86	2.78	2.78
Total	2.92^{c} (0.21)	3.45^{b} (0.26)	3.38^{abc} (0.27)	3.42^{ab} (0.34)

[a–c]Different superscripts indicate statistical difference ($P < 0.05$) between systems as based only on A uncertainties, which were considered to vary between systems.

[1]The SD (in parentheses) were based on A and B uncertainties. The B uncertainties were considered to be similar between the systems.

offset the production of synthetic fertilizers or N-fixing rotational crops. This also occurred in land occupation, especially in organic systems in which the N source was from fixation by legumes.

Buildings provided a relatively large contribution to the abiotic resource use category. This was most marked in lower density housing systems, even though the specific burdens were lower per unit area for these types of housing. In the category of land occupation, the organic system had clearly higher values than that of any other system. This was caused mainly by the higher land area requirement for feed production of organic crops, and to a smaller extent, by the big ranging area of organic birds. The land requirements of the nonorganic systems were roughly proportional to their productivity.

The results also show that, in all categories, most of the burdens originated from the laying stage and only a small proportion (generally around 1%) was associated with breeders (Tables 6 to 10).

Thus far, the LCA method has not been used widely to compare the environmental impacts of egg production systems (de Vries and de Boer, 2010; Xin et al., 2011). In an earlier study, Williams et al. (2006) analyzed the environmental impacts per 20,000 eggs (approximately 1,000 kg) in the cage, nonorganic free range, and organic systems in the UK. There were some differences in the results of that and the present study partly because of more up-to-date detailed data being made available to the researchers than was available to Williams et al. (2006). In their study, the environmental burdens generally followed the differences in production efficiency between the systems; that is, the cage systems had the lowest impacts and the organic system the highest. This trend was not as clear in the present study. For example, the relative differences in GWP were much smaller between the systems than in Williams et al. (2006). This was caused by the fact that in the present study, the differences in, for example, farm energy use between the systems did not follow a similar trend as the differences in FCR, and therefore the impacts partly counterbalanced each other in the different systems. Similarly, in the present study, the GWP per 1,000 kg of organic layer feed was slightly lower than that for the nonorganic feed, which reduced the otherwise high feed burdens of the organic system (where the feed consumption and FCR were the highest).

Table 8. Eutrophication potential (kg of PO_4 equivalent) for the 4 different systems considered per 1,000 kg of eggs[1]

Material or activity	Cage	Barn	Free range	Organic
Feed + water	7.80	8.23	8.76	21.90
Electricity	0.00	0.00	0.00	0.00
Gas + oil	0.01	0.01	0.02	0.02
Housing + land	3.43	3.83	4.20	4.84
Manure + bedding	7.23	8.24	9.05	10.84
Breeder	0.29	0.21	0.21	0.22
Pullet	2.67	2.62	2.68	7.63
Layer	15.51	17.49	19.13	29.76
Total	18.47^{c} (1.57)	20.32^{b} (1.78)	22.03^{b} (2.01)	37.61^{a} (4.21)

[a–c]Different superscripts indicate statistical difference ($P < 0.05$) between systems as based only on A uncertainties, which were considered to vary between systems.

[1]The SD (in parentheses) based on A and B uncertainties. The B uncertainties were considered to be similar between the systems.

Table 9. Acidification potential (kg of SO_2 equivalent) for the 4 different systems considered per 1,000 kg of eggs[1]

Material or activity	Cage	Barn	Free range	Organic
Feed + water	8.25	8.69	9.24	9.72
Electricity	0.99	1.98	0.84	0.98
Gas + oil	0.15	0.21	0.29	0.25
Housing + land	18.45	20.61	22.58	26.04
Manure + bedding	25.30	27.95	31.17	54.65
Breeder	0.75	0.55	0.52	0.54
Pullet	7.94	7.82	8.02	26.23
Layer	44.45	51.06	55.59	64.86
Total	53.14^c (5.23)	59.43^b (5.99)	64.13^b (6.90)	91.63^a (8.66)

[a–c]Different superscripts indicate statistical difference ($P < 0.05$) between systems as based only on A uncertainties, which were considered to vary between systems.

[1]The SD (in parentheses) were based on A and B uncertainties. The B uncertainties were considered to be similar between the systems.

In the Netherlands, Mollenhorst et al. (2006) compared the environmental impacts and other sustainability indicators in 4 egg production systems. Also in their study, feed was the main source of environmental impacts and the differences in the impacts between the systems followed the differences in the FCR. The absolute values of GWP were slightly higher in the study by Mollenhorst et al. (2006) compared with those in the present study, but the primary energy use was lower. The EP and AP were generally of similar magnitude in both studies. However, as stated by Leinonen et al. (2012), direct comparison between separate LCA studies for agricultural products is not always possible because differences may occur in methodology, functional units, system boundaries, and impact categories, for example.

It must be stressed that the results presented in the present study do not claim to be the average of all UK egg production systems. The data are broadly representative, but performance will vary between producers with whatever system is in use. The farm activity data were mainly from about 1 year's operations, which can be affected by weather and other random influences. Although statistical differences were determined between some systems and burdens, these were simply based on the data available.

In general, comparison between different studies or different systems in a single study is not feasible if the range of uncertainty in the results is not available. Therefore, it is quite surprising that uncertainly analyses have very rarely been applied in LCA studies for agricultural products, despite the fact that comparison between different systems has generally been the aim of such studies. Wiltshire et al. (2009) developed a method for calculating the uncertainties for GHG emissions from food production, and this method was also applied for other environmental impacts in the present study and in a similar study for environmental impacts of broiler production in Leinonen et al., (2012). The mathematical models for the systems used in these studies are complex, include several submodels, and a large number of parameters and input variables that have their own uncertainties. Therefore, it was not possible to calculate the uncertainties using analytical methods, such as partial differential equations, as demonstrated by Leinonen et al. (2006). Instead, an approach based on Monte Carlo simulations was required.

The first step in the uncertainty analysis is to quantify the different types of errors related to each parameter and input variable and to define their probability distributions. In the present study, errors related to the main input variables were based directly on the data provided by the UK egg production industry, and the errors in the emissions factors were based on values obtained from literature. When the distribution of each input is known, the Monte Carlo method can be directly applied to randomly select values of the inputs for each separate simulation and to produce the probability distributions of the outputs that are needed for system comparison. However, there are 2 important aspects in the uncertainty calculation that can potentially lead to overestimation of the total uncertainty if not taken into account. Both are related to intercorrelation between model inputs.

First, some of the errors vary between different systems under consideration (A errors), but others can be considered to be the same across the systems (B errors). Examples of B errors include emission factors

Table 10. Abiotic resource use, land occupation, and pesticide use for the 4 different systems considered per 1,000 kg of eggs

Burden	Cage	Barn	Free range	Organic
Abiotic resource use, kg of antimony equivalent	9.11	14.62	15.38	20.25
Land occupation, ha	0.40	0.42	0.51	1.69
Pesticide use, dose-ha	2.07	2.20	2.33	0.09

from housing and some parameters of the animal production model. It is assumed in the analysis that if an error with a certain direction and magnitude occurs in any of these parameters in one system, it also has a similar effect in the other systems. Therefore, when the differences between the systems are analyzed statistically, B errors should not be included in the calculations, otherwise the within-system variation would be overestimated and the significance in the differences between the systems would be underestimated.

Second, variations in some of the different input variables can be correlated within a single system. For example, variables related to animal growth and production, food intake, manure production, and nutrient output are all related to each other; that is, a change in one variable is likely to cause a change of a certain direction in another. The advantage of using mechanistic submodels for animal and crop production, as was done in the present study, is that these relationships are automatically built into the results. During each Monte Carlo simulation, any random change in one input variable would cause a realistic response in the others. This prevents the overestimation of the total uncertainty, which would occur if the errors in each input are considered to be completely independent of each other.

Although conventional laying cages were the most common method of commercial egg production in the UK for many years, their use has declined dramatically in recent years. The popularity of alternative housing systems, in particular free-range and organic housing, has risen in response to consumer interest in more extensive forms of egg production and especially as the deadline of January 1, 2012, approaches. Some cage producers have converted their cages or installed new enriched (colony) cage systems; it is expected that the UK will be among those European producers who comply fully with the legislation. However, it remains to be seen whether the number of UK hens in enriched cages will be the same as those in conventional cages. Currently, it is unknown what the potential environmental impacts of such systems would be, but providing that relevant data are generated, the approach used here could also be applied for them. This would enable comparisons between the alternative cage and other systems in terms of their environmental impacts and allow for some conclusions in relation to the environmental impacts of higher welfare systems. The debate over the trade-offs between environmental impacts and animal welfare is in its infancy (Moorehouse et al., 2009), as is the debate over trade-offs between environmental impacts and sensory properties of livestock products.

As a conclusion, the current study found relatively large differences in many categories of the environmental impacts between the 4 different egg production systems; generally, these reflected the differences in the efficiency in production, feed consumption (and related production of manure), and material and energy use. In addition to the general differences observed between the systems, the uncertainty analysis showed that there can be a large variation in the impacts between different production units representing the same systems, depending on, for example, the production efficiency, composition of feed used, and farm energy use. The methodology developed in the current study can be readily applied for single production units to quantify the impacts of potential improvements in the production activities in order to reduce the burdens to the environment. The same method with small modifications is also applicable for other agricultural products, as demonstrated in the case of broiler meat by Leinonen et al. (2012).

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APPENDIX

Table A1. Standard and free-range layer diet (%)

Ingredient	Starter (0–6 wk)	Rearer (6–15 wk)	Developer (15–20 wk)	Early lay (20–35 wk)	Late lay (35 plus wk)
Wheat	63.52	67.11	67.53	64.06	68.53
Wheat feed	7.35	9.26	12.18	3.34	
NGM[1] HiPro soy	20.09	9.69	6.67	14.51	11.95
Sunflower	4.00	10.00	10.00	6.00	7.00
Vegetable (mix) blend	1.25	0.75	0.50		1.55
H E Blend (soy oil)	0.50			1.76	
Fine limestone	1.40	1.40	1.40	9.00	9.70
Mono-dicalcium phosphate	0.85	0.80	0.80	0.36	0.31
$NaHCO_3$ (bulk)	0.31	0.34	0.32	0.25	0.26
Salt	0.15	0.14	0.16	0.17	0.16
Lysine HCl	0.16	0.18	0.14	0.13	0.15
DL-Methionine	0.14	0.05	0.02	0.14	0.11
Enzyme (NSP[2]/single phytase)	0.03	0.03	0.03	0.03	0.03
Pullet starter premix	0.25				
Pullet grower premix		0.25	0.25		
Layer premix				0.25	0.25
Total	100.00	100.00	100.00	100.00	100.00

[1]NGM = nongenetically modified.

[2]NSP = nonstarch polysaccharide.

Table A2. Nutrients (%) and energy (MJ/kg) in standard and free-range layer diets

Item	Starter	Rearer	Developer	Early lay	Late lay
ME, MJ/kg	12.00	11.60	11.60	11.40	11.30
CP	18.50	15.80	15.00	15.80	14.80
Lysine	0.98	0.78	0.68	0.79	0.74
Methionine	0.41	0.30	0.26	0.38	0.34
Methionine+cystine	0.74	0.60	0.55	0.67	0.62
Tryptophan	0.24	0.20	0.19	0.21	0.19
Threonine	0.64	0.53	0.49	0.54	0.50
Arginine	1.18	0.98	0.91	0.99	0.91
Valine	0.83	0.70	0.66	0.71	0.66
dig[1] lysine	0.88	0.70	0.60	0.71	0.66
dig methionine	0.38	0.28	0.24	0.36	0.32
dig methionine+cystine	0.67	0.54	0.49	0.61	0.56
dig tryptophan	0.21	0.18	0.17	0.18	0.17
dig threonine	0.54	0.44	0.41	0.46	0.43
dig arginine	1.06	0.87	0.80	0.89	0.82
dig valine	0.73	0.62	0.58	0.63	0.59
Ca	0.97	0.96	0.96	3.80	4.00
P[2]	0.57	0.57	0.57	0.42	0.38
Available P[2]	0.42	0.42	0.42	0.30	0.25
Na	0.17	0.18	0.18	0.16	0.16
Cl	0.22	0.23	0.23	0.22	0.23

[1]dig = digestible.

[2]This is as elemental P, not PO_4 or P_2O_5.

Table A3. Organic layer diet (%)

Ingredient	Grower (0–6 wk)	Rearer (6–20 wk)	Early lay (20–35 wk)	Late lay (35 plus wk)
Organic wheat	62.67	63.85	44.21	48.15
Organic maize	3.00	3.00	18.00	15.00
Organic wheat feed		6.00		5.00
Organic sunflower expeller	10.00	10.00	12.00	6.00
Organic soy expeller	15.00	9.00	9.60	9.60
Prairie meal	2.00	2.00	2.00	3.00
Potato protein	2.80	2.80	2.40	1.40
Organic soy oil	1.00	0.50	1.00	0.50
Monocalcium phosphate	1.18	1.00	1.00	0.75
Betaine	0.10	0.10	0.10	0.10
Limestone	1.50	1.00	9.00	9.75
Salt	0.30	0.30	0.30	0.30
Sodium bicarbonate	0.20	0.20	0.14	0.20
Pullet starter premix	0.25			
Pullet grower premix		0.25		
Layer premix			0.25	0.25
Total	100.00	100.00	100.00	100.00

Table A4. Nutrients (%) and energy (MJ/kg) in organic layer diets

Item	Grower	Rearer	Early lay	Late lay
ME, MJ/kg	12.40	12.20	11.55	11.40
CP	19.50	17.50	16.50	15.50
Lysine	0.87	0.72	0.73	0.64
Methionine	0.37	0.35	0.34	0.30
Methionine+cystine	0.75	0.70	0.67	0.62
Tryptophan	0.24	0.22	0.20	0.18
Threonine	0.72	0.64	0.64	0.55
Arginine	1.15	1.03	0.99	0.89
Valine	0.94	0.85	0.83	0.75
dig[1] lysine	0.76	0.66	0.64	0.56
dig methionine	0.30	0.28	0.28	0.25
dig methionine+cystine	0.60	0.56	0.53	0.50
dig tryptophan	0.20	0.18	0.16	0.15
dig threonine	0.62	0.55	0.54	0.49
dig arginine	1.01	0.90	0.88	0.78
dig valine	0.83	0.75	0.73	0.66
Ca	0.95	0.72	3.75	4.00
P	0.60	0.58	0.54	0.48
Available P	0.40	0.34	0.33	0.30
Na	0.18	0.18	0.17	0.18
Cl	0.25	0.25	0.24	0.24

[1]dig = digestible.

Table A5. Layer premix specifications (per kg of premix)

Ingredient (unit)	Pullet starter	Pullet grower	Layer
A, IU	10,000	8,000	10,000
D, IU	3,000	2,000	3,000
E, IU	30	30	60
K, mg	3	3	3
B_1, mg	1	1	1
B_2, mg	6	6	6
B_6, mg	3	2	3
B_{12}, μg	15	10	15
Folic, mg	1	0.5	1
Calcium-D-pantothenate, mg	8	7	8
Nicotinic, mg	30	30	30
Biotin, mg	0.5	0.25	0.5
Choline chloride,[1] mg	100	100	100
Fe, mg	25	25	25
Cu, mg	5	5	5
Mn, mg	100	100	100
Zn, mg	60	60	60
Cobalt, mg	0.1	0.1	0.1
Iodine, mg	0.5	0.5	0.5
Se, mg	0.2	0.2	0.2

[1]Not applicable to organic diets.