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

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ABSTRACT The aim of this study was to apply the life cycle assessment (LCA) method, from cradle to gate, to quantify the environmental burdens per 1,000 kg of expected edible carcass weight in the 3 main broiler production systems in the United Kingdom: 1) standard indoor, 2) free range, and 3) organic, and to identify the main components of these burdens. 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 the useful outputs. The analysis was based on an approach that applied a structural model for the UK broiler industry and mechanistic submodels for animal performance, crop production, and major nutrient flows. Simplified baseline feeds representative of those used by the UK broiler industry were used. Typical UK figures for performance and mortality of birds and farm energy and material use were applied. Monte Carlo simulations were used to quantify the uncertainties in the outputs. The length of the production cycle was longer for free-range and organic systems compared with that of the standard indoor system, and as a result, the feed consumption and manure production per bird were higher in the free-range and organic systems. These differences had a major effect on the differences in environmental burdens between the systems. Feed production, processing, and transport resulted in greater overall environmental impacts than any other components of broiler production; for example, 65 to 81% of the primary energy use and 71 to 72% of the global warming potential of the system were due to these burdens. Farm gas and oil use had the second highest impact in primary energy use (12–25%) followed by farm electricity use. The direct use of gas, oil, and electricity were generally lower in free-range and organic systems compared with their use in the standard indoor system. Manure was the main component of acidification potential and also had a relatively high 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, broiler, energy use, carbon footprint

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INTRODUCTION

There is an increased worldwide interest in quantifying resource use and environmental burdens involved in the production of different agricultural commodities. This reflects concerns about environmental impacts, especially their contribution to climate change and the sustainability of resource use (Steinfeld et al., 2006). Broiler production has been identified as being relatively environmentally efficient (per unit output) compared with the efficiency of other animal systems (Williams et al., 2006). However, like all agricultural systems, any current poultry system has the scope to be improved, and thus, there is the potential to reduce its environmental impacts.

Among different categories of environmental impacts, the term carbon footprint has received most of the current attention (Wiedmann and Minx, 2008). This is the aggregated greenhouse gas (**GHG**) emissions per unit of a commodity, and producers are increasingly being asked by their customers to provide such data. However, GHG emissions are not the only burden that broiler production places on the environment. Ammonia and particulate emissions emerge from animal housing (Wathes et al., 1997), and energy is used directly

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for feeding, heating, lighting, and ventilation. Together with manure management, the production, processing, and delivery of feed may also incur (for example) nitrate leaching and pesticide use as well as their aforementioned use of energy and creation of GHG emissions (Williams et al., 2010).

Various environmental assessment methods have been developed and applied to livestock production systems (Halberg et al., 2005a,b; Lilywhite et al., 2007; BSI, 2008), such as ecological, environmental, and carbon footprinting, nutrient surpluses per hectare, specific gaseous emissions, and environmental life cycle assessment (**LCA**). Most methods differ in their underlying assumptions, system and geographical boundaries, and their purpose; for example, reducing nitrate leaching per hectare or improving input-output efficiencies. However, LCA is the most holistic method available, and thus, overcomes many of the limitations of the other assessment methods (Guinée et al., 2002; BSI, 2006). For this reason, LCA is the methodology favored by major organizations, such as the United Nations Environment Program (http://www.uneptie.org/scp/) and sectors of the broiler industry. The LCA method considers the environmental burdens and resource use in the production and exploitation of a commodity in defined boundaries. This can be from cradle to grave, which includes the retail, consumption, and disposal stages, but it is also common and pragmatic for agricultural production to stop the analysis at the farm gate, thus, cradle to gate.

The main broiler production systems in the UK include 1) standard indoor, 2) free range, and 3) organic. According to the Defra (2007) statistics, the total broiler chicken populations in these systems in the UK were 101, 4.4, and 1.8 million, respectively. The aim of the current study was to apply the LCA method from cradle to gate in order to quantify the environmental burdens of each of these 3 systems in the UK, and hence, to identify the main opportunities for reducing these environmental impacts within each system.

MATERIALS AND METHODS

LCA General Principles

The LCA analyses of production systems systematically accounts 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, which 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 assessment 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 3 main broiler production systems in the UK (standard indoor, free range, and organic), and hence, to identify the main opportunities for reducing these environmental impacts within each system. The intended audiences were the broiler producers, the agri-environmental scientific community, and other stakeholders in the supply and consumption chain. The functional unit was 1,000 kg of expected edible carcass weight at the farm gate; it was defined as live weight × the killing-out percentage (it did not include feather, gut, feet, and so on, or edible organs, such as the liver). The functional unit did not consider the actual burdens of slaughter or processes or any losses that occur between the farm gate and the end of the processing line. All upstream inputs were included in the analysis (Figure 1).

Economic allocation (Williams et al., 2006) was generally used to partition the burdens between coproducts (e.g., human food and animal feed) in feed crop production and between broiler meat and spent broiler breeder meat, which can be seen as a byproduct of a system in broiler production. Some burdens, such as nitrate leaching from crops, were derived from a crop-soil simulation model and calculations of leaching in proportion to the N surplus for each crop.

Resources, Burdens, and Impacts

All inputs were traced back to primary resources; for example, electricity (an energy carrier) was generated

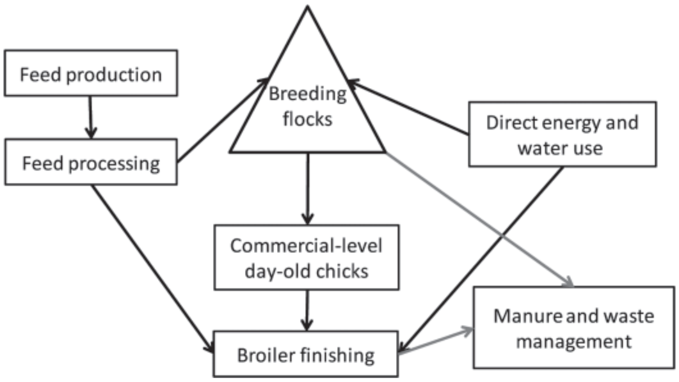

Figure 1. The structure and the main components of the broiler production systems assessed in the study.

from primary fuels: coal, natural gas, hydro-power, and uranium. The overheads of extraction, distribution, and delivery of all energy carriers were included in their own life-cycle inventories (**LCI**). One unit of delivered electrical energy uses about 3 units of primary energy. The overheads of diesel are lower, about 1.3 times the delivered process energy. The LCI data for energy carriers came from the European reference life-cycle database of the European Union (Joint Research Centre, 2010).

The LCI includes many terms relating to the consumption of resources, emissions to the environment, and degradation of the environment; for example, land used in quarrying. The impacts, such as nonrenewable energy use or GHG emissions, are burdens on the environment. In turn, these have impacts, which are sometimes quantified as potential impacts (BSI, 2006). For example, GHG emissions have an environmental impact: global warming potential (**GWP**). Similarly, leached nitrate is a burden, but eutrophication is the impact. Most burdens were aggregated into potentials (or other indicators) for causing impacts, such as GWP, eutrophication potential (**EP**), acidification potential (**AP**), ozone depletion potential, and photo-chemical smog formation potential. Some of these have a universal impact, such as GWP, whereas others, such as AP, are more specific to the location and the sensitivity of the receiving environment but are typically defined on a national or continental basis (detailed in Appendix 1).

In some LCA studies, all impacts are converted into unified indicators for the impacts on human health or eco-toxicity. This has not been applied in the current study, so the principal outputs were the LCI of the production systems.

Systems Approach

The general approach in the current study was with systems modeling of production systems 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. Empirical data were used where no functional relationships were available.

Audsley et al. (1997) conducted a study to harmonize the application of LCA in agriculture. The current study followed the principles therein. Williams et al. (2006, 2010) followed Audsley et al. (1997) in 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 carbon footprinting (BSI, 2008). The systems modeled included crop production, noncrop nutrient production, feed processing, breeding (including maintaining breeding flocks, hatching, and pullet rearing), production (including broiler rearing and finishing), energy and water use in housing, feeding, and gaseous emissions, manure management, and general waste management.

The principles of the approach used in the present study were close to Williams et al. (2006), but there were differences: noncrop feeds, such as pure amino acids and fish meal, were included in our analysis, and particularly, the bird performance (growth, food intake, and nutrient excretion) was modeled mechanistically (see Animal Growth and Production Submodel section below). In addition, some new crop 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 taken into account (see Crop and Manure Submodel section below). The sources of data on energy carriers were updated from the European reference life-cycle database, and some detailed processes were revisited. The emission factors for GHG and GWP were 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.

Broiler 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 (broiler meat) 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, hatching and rearing) was required was found by linear equations that describe the relationships that link the activities together.

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 (e.g., the number of birds), of each activity i that produced the desired amount of output Z (e.g., broiler meat),

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

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 chicks from hatcheries must equal the demand of birds in the rearing system and allow for mortalities.

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

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

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,

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

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,

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

or activity,

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

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, food intake, and excreta composition. This allows variations in production methods to be analyzed when no empirical data are available. These can include variations in the length of production cycle, feed composition, or 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 plant 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 (age, BW, 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 includes requirements for both production (body growth) and maintenance.

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 of birds was determined by the first limiting amino acid in the feed. The growth rate of the birds and the energy requirement of maintenance vary between the production systems, and therefore the model, needed to be calibrated for its application in these systems. The growth-rate function of the mechanistic animal submodel was adjusted according to the growth-rate figures provided by the UK broiler industry. The food intake was then calibrated for each production system by using the principle of energy balance. The energy in the consumed feed was allocated to body growth, excreta, and spillage, based on estimates obtained from the industry and from literature. The energy obtained from feed and not included in any of these components had to be allocated to maintenance, and in order to maintain the energy balance, the maintenance function in the model was adjusted to match the level of feed intake obtained from the industry data. This also took into account additional food intake from foraging in free-range and organic systems.

The total consumption of each type of feed during the production cycle was quantified from the daily values calculated by the model, and thus, the environmental burdens of the feeds were calculated from total consumption of each feed ingredient. For ingredients produced from arable crops (a major part of the diets), the environmental burdens were quantified using a separate submodel 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 in the animal body 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 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 free-range and organic birds, the proportion of nutrients excreted outside the house was not credited to crop production, given that, according to the UK broiler industry data, the entire ranging area was grassland in both systems and not used for producing commercial crops.

The primary output of the mechanistic production model was the daily feed intake and manure production of one typical bird at any stage of the production cycle. However, mortalities and their effect on the total feed consumption were also taken into account (all other burdens were scaled pro rata). These were calculated on the basis of typical mortality rates for each production system.

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. (2006, 2010). This approach uses systems modeling and a long-term perspective to derive yields and nitrate leaching. Direct nitrous oxide emissions were calculated using IPCC (2006) tier-one emission factors. All major crops used for production of poultry feed were modeled. Most feed crops were produced in the UK but some 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 (Williams et al., 2006). The approach includes all major terms for crop production; that is, cultivation, plant protection, fertilization (field work and fertilizer production), seed production, harvesting, cooling, drying, and storage.

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 certified and 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 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), which occur during housing, storage, and land spreading. Manure management also uses energy, and these burdens were 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 either as 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, with rock P and K used instead of triple superphosphate and potassium chloride.

Production Systems and Sources of Data

Three different broiler production systems were compared in the current study: standard indoor, free range, and organic. Data on these systems were provided by major broiler production companies that were stakeholders in this study and were considered to represent the overall UK broiler industry. The bird genotypes applied in different systems and the representative production figures as provided by the UK broiler industry are presented in Table 1. These figures include data, such as average finishing age and finishing weight of broilers, stocking density, average feed intake, and mortality. The proportion of spilled feed was not based on actual measurements but was an estimate supplied by the industry and consistent with literature (Kyriazakis, 2011). However, it should be noted that the spilled feed was included in the total observed feed consumption and the nutrients in spilled feed were added to broiler litter (similarly as the nutrients excreted by the birds). Therefore, even though the estimate of spillage may be inaccurate, it has no significant effect on the overall model output because the spilled feed has a similar effect in the systems as the feed actually eaten by the birds.

Simplified baseline feeds representative of those used in the UK were formulated using information provided by the industry. The countries of origin of each feed ingredient were also determined on the basis of the industry data. Separate feeds were used for standard broilers, free-range broilers, organic broilers, and broiler breeders. The details of the feeds are presented in Appendix 2 in Tables A1, A2, A3, A4, A5, and A6. In all production systems, birds were subjected to a standard vaccination program for UK broilers. Full and detailed burdens of vaccines were not calculated but preliminary estimates based on data received from the industry suggested that these contributed to <0.25% of primary energy use or GWP.

General information on the industry structure, including broiler rearing, finishing, breeding, and feed processing was obtained from the UK broiler production industry. For detailed information about different activities considered in the current study, typical production units were selected to represent each production system and the activity data obtained from these units are presented in Table 1. The energy consumption for heating, lighting, ventilation, and feeding (Table 1) was based on average data from typical farms from 2009 and 2010 as provided by the industry (separate units for rearing and finishing in the case of free-range and organic broilers). Information about the type and amount of bedding was also obtained from the industry. In this study, it was assumed that all litter was trans-

Table 1. Typical production and food intake figures and genotypes used by the different UK broiler production systems as provided by the UK broiler industry and applied in this study

Variable	Standard	Free range	Organic
Genotype	Ross 308	Ross Rowan	Hubbard JA57
Average final age (d)	39	58	73
Average final weight (kg)	1.95[1]	2.06	2.17
Average feed intake (kg/bird)	3.36	4.50	5.75
Average mortality (%)	3.5	4.7	4.1
Estimated food spillage (%)	2	2	2
Time of rearing (d)	—	28	35
Indoor stocking density (birds/m^2), rearing	—	26.0	22.6
Indoor stocking density (birds/m^2), finishing	20.4	12.9	9.9
Outdoor stocking density (birds/m^2), finishing	—	0.32	0.25
Number of birds/house, rearing	—	40,000	24,000
Number of birds/house, finishing	28,500[1]	4,800	3,700
Type of bedding	Wood shaving	Wood shaving/straw	Wood shaving/straw
Amount of bedding (kg/bird)	0.165	0.22	0.32

[1] 25% of birds were removed by thinning at a BW of 1.8 kg. The final weight of remaining birds was 2.0 kg.

ported for soil improvement, which is a general practice in the UK broiler systems. Broiler litter is sometimes burned as a fuel in power stations, but this option requires a separate analysis of its own.

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

The model inputs include certain uncertainties (e.g., potential measurement errors, variation in activity and production data), and the impact of these uncertainties on the model output must be quantified to make it possible to evaluate differences between the 3 systems under consideration and also to compare the results with other studies. A Monte Carlo approach was applied in the present study to quantify these uncertainties. 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 analyses because sufficient data on their uncertainties were not available.

The range of variation between farms in the energy use data was obtained from the industry. As based on given maxima and minima, and assuming that the energy consumption of most farms is closer to the average than to the extremes, triangular distributions were applied. These distributions for electricity and liquid propane gas 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 final age resulted in higher average final weight, and further, higher final weight resulted in higher feed intake. The correlations between these figures were built into the mechanistic animal production submodel, and therefore, were automatically taken into account in the uncertainty analysis (see Animal Growth and Production Submodel section above). Note that ignoring such positive correlations between these variables and assuming the uncertainties of the inputs to be independent of each other (e.g., assuming that a combination of high BW and low feed intake would be as likely as high BW combined with high feed intake) would lead to an overestimation of the total uncertainty. Additional random variation was also included in the model parameters, describing growth rate and maintenance energy requirement, both of which were assumed to follow a normal distribution in the Monte Carlo simulations. The magnitude of this variation was adjusted to match the overall variation in the industry production data; for example, BW and feed intake. 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 (with normal distribution) in the nutrient content of the animal body. In general, normal distributions were used for variables related to animal production and performance because these were considered to be based on biological processes. One exception was the final age of free-range broilers that has an absolute minimum (56 d) determined by regulations.

The lognormal 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., 2010). 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). Alpha errors were considered to vary between systems, and therefore, were taken into account in statistical analyses of the differences between the systems. For example, variation between farms in production, feed intake, and energy use figures were all considered to represent A errors. 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. For example, the uncertainty of the modeled nutrient content of the chicken body was considered to be similar in all systems (B error). As a result, the amount of nutrients in broiler manure included both A errors (related to the amount of feed intake) and B errors (related to nutrients retained in the body).

Detailed worked examples of the approach, including sources of uncertainties, are given in Wiltshire et al. (2009), which addresses uncertainty estimation for product carbon footprinting under PAS2050 (BSI, 2008). The methods align closely with those in the international standards for uncertainty analysis (JCGM, 2008a,b).

In Table 2, the CV is presented for main input variables. 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 environmental 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 $(1 - \alpha)$ confidence level. The probability level under consideration is 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 are 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, or transport of ingredients); gas and oil (consumed at the farms and hatcheries, not including feed production, processing, or transport of ingredients); housing and land (including 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, or 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 commercial broiler generation) and commercial broilers.

Table 2. Uncertainties (CV) and their distributions of the main variables for broiler production systems in the life cycle assessment model

Variable	CV A[1] (%)	CV total (A[1] + B[2]) (%)	Distribution
Final age	2 to 4	2 to 4	Normal, Triangular
BW	2 to 4	2 to 4	Normal
Feed intake	3 to 5	3 to 5	Normal
Amount of N in manure	3 to 6	3 to 9	Normal
Amount of P in manure	3 to 5	3 to 7	Normal
Amount of K in manure	3 to 5	3 to 5	Normal
Farm electricity consumption/bird	3 to 14	3 to 14	Triangular
Farm liquid propane gas consumption/bird	10 to 17	10 to 17	Triangular
Mortality	15	15	Normal
Killing out %	5	5	Normal
Environmental impacts/1,000 kg of feed	1 to 6	4 to 18	Normal
N_2O emission factor	NA[3]	37	Lognormal
NH_3 emission factor	NA	28	Lognormal
CH_4 emission factor	NA	30	Lognormal
Transport distance	NA	3	Normal
Proportion of ammoniacal nitrogen in excreta	NA	2	Normal
Denitrification factor	NA	5	Normal
Feed spillage	5	5	Normal
Breeder egg production	4	4	Normal

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

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

[3] NA = not applicable.

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

Variable	Standard	Free range	Organic
Hatched chicks[1]	817	793	790
Finished broilers	778	747	750
Feed consumed[1] (kg)	2,913	3,645	4,518
Water used[1,2] (m^3)	4.41	6.86	7.03

[1] Includes broilers and breeders.

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

RESULTS AND DISCUSSION

The number of birds required to produce the expected edible carcass weight of 1,000 kg was higher in the standard indoor system compared with that in the free-range and organic systems (Table 3). This was caused by the finishing weight being lowest in the standard indoor system; the mortality of the birds was actually higher in the free-range and organic systems. On the other hand, the length of the production cycle was much longer in free-range and organic systems compared with that in the standard indoor system, and as a result, the feed consumption per bird was higher in these systems. This has a major impact on the trends in environmental burdens, as discussed below.

In addition to different amounts of feed consumption, the composition of feeds also varied between systems, resulting in different environmental burdens per equal amount of feed. The burdens for feeds applied in different systems are presented in Table 4. Standard broiler feed had the highest burdens in the categories of GWP and AP per unit of feed, and organic feed had the highest primary energy use, EP, and land occupation burdens.

To demonstrate the relative importance of single feed ingredients, the breakdown of burdens (GWP is presented here as an example) for the feed used in different systems is shown in Table 5. The results show that soy had the highest proportion of GWP of feeds in standard and free-range systems. This was mainly caused by GHG release as a result of land-use changes, which were assumed to occur in nonorganic crop production (where the exact origin of the crop is not known) but not in organic crop production (certified origin). In standard and free-range broiler feeds, vegetable oil (largely affected by land-use changes in the production of palm oil) and pure amino acids also had a high proportion of GWP as well as fish meal in standard broiler feed. The environmental burdens of fish meal depend strongly on whether this ingredient is produced from purposely caught fish for animal feed or from by-products from fish aimed for human consumption. In this study, it was assumed that 50% of the fish meal came from purposely caught fish and 50% from by-products, as indicated by the data provided by the UK broiler industry.

The main burdens from each whole system per 1,000 kg of expected edible carcass weight are listed in Tables 6, 7, 8, 9, and 10. The results show that the standard and free-range systems had lower primary energy use compared with that of the organic system, and the differences between the organic and nonorganic systems were statistically significant ($P < 0.05$). The organic system had significantly higher GWP than that of the standard indoor system ($P < 0.05$). The EP and AP were significantly higher ($P < 0.05$) in the organic system compared with those in the other systems. The organic system also had the highest abiotic resource use and land occupation, but the pesticide use in the organic system was very low, about 8% of the amount in the nonorganic free-range system. Pesticides in the organic system were used in the production of breeder feed only.

Tables 6 to 10 also show the breakdown of the environmental impacts by material and energy flow as well as by activity. Although any specific sensitivity analysis was not carried out in this study, these results directly show the relative impacts of the main inputs to the systems; for example, feed, electricity, gas, and oil. Feed caused higher overall environmental impacts than any other materials involved in production; for example, 65 to 81% of the primary energy use and 71 to 72% of the GWP of the system. Water contributed <0.2% to the feed and water group. In many impact categories, the environmental burdens originating from the feed were highest in the organic system (partly because of the high feed conversion ratio), and this was also a major cause of the overall differences between

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

Burden[1]	Standard	Free range	Organic
Primary energy used (GJ)	5.78	5.05	7.41
GWP_{100} (1,000 kg of CO_2e)	1.11	1.03	0.91
EP (kg of PO_4 equivalent)	3.69	3.25	7.69
AP (kg of SO_2 equivalent)	4.05	3.66	3.88
Pesticide use (dose-ha)	1.00	0.99	0.03
Abiotic resource use (antimony equivalent, kg)	2.85	2.52	3.47
Land occupation (ha)	0.20	0.19	0.59

[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 broiler feeds consumed during the whole production cycle

Standard	%	Free range	%	Organic	%
Soy meal	41.9	Soy meal	45.1	Wheat	62.8
Wheat	28.3	Wheat	33.7	Soy meal	13.5
Vegetable oil blend	9.3	Vegetable oil blend	8.2	Processing[1]	6.8
Rapeseed	6.6	Processing[1]	4.1	Soy whole	6.3
Processing[1]	3.8	Soy whole	3.8	Sunflower expeller	4.8
Soy oil	2.9	Lysine	1.3	Potato meal	3.2
Fishmeal	2.8	Methionine	1.2	Mono-calcium phosphate	1.7
Lysine	1.6	Mono-calcium phosphate	0.9	Soy oil	0.5
Methionine	1.3	Threonine	0.7	Betaine	0.3
Threonine	0.8	Soy oil	0.7	Limestone	0.1

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

the organic and the other systems. However, in many categories, the differences in the feed impacts between the systems were not directly proportional to the differences in feed intake alone, given that the composition of the feed in different systems also had a major impact. For example, the GWP was affected by relatively high environmental impact of some ingredients, such as nonorganic soy, palm oil, fish meal, and pure amino acids, in the standard and free-range broiler feed. On the other hand, organic feed generally had a much higher impact than that of the nonorganic feed in several other categories. This difference was partly caused by a larger proportion of organic ingredients being produced overseas and imported to the UK compared with the nonorganic feed and also by the generally smaller yields of organic crops. For example, all of organic feed wheat was imported from countries such as Romania and the Ukraine, and the transport distance roughly doubled the total energy use. The EP of organic feed was especially high. This was caused by higher leaching of nutrients in organic crop production. Although leaching per land area could be lower compared with that in nonorganic production, a lower yield and higher land-use requirement resulted in higher overall EP for organic crops.

Gas and oil (used mainly for heating) had the second highest impact in primary energy use (12–25%) followed by electricity (mainly ventilation, feeding, and lighting). The use of gas, oil, and electricity was generally lower in free-range and organic systems compared with that in the standard indoor system. This was because heating was not usually used in the free-range and organic finishing farms, and during rearing, the temperature was kept lower than that in the standard indoor system. Furthermore, these farms usually had natural ventilation that was sometimes supplemented by cooling fans.

Manure was the main component of AP and also had relatively high EP. This was mainly a result of ammonia emissions, which contributed to both these potentials, together with nitrate leaching (after land application), which only affected EP. The AP from manure was especially high in the organic system because the manure production from the organic birds was high due to a long production cycle. Also, the nitrogen content of the feed and manure was higher compared with those 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 offset the production of synthetic fertilizers. This also occurred in land occupation, especially in organic systems in which the source of N was from fixation by legumes. Otherwise, the organic system had a clearly higher value

Table 6. Primary energy use (GJ) for the 3 different systems considered per 1,000 kg of expected edible carcass weight

Material or activity	Standard	Free range	Organic
Feed + water	16.4	18.2	32.8
Electricity	2.82	2.53	2.88
Gas + oil	6.31	5.05	4.64
Housing + land	0.23	0.33	0.48
Manure + bedding	−0.37	−0.44	−0.47
Breeder	1.93	1.84	1.43
Broiler	23.44	23.81	38.91
Total[1]	25.37[b] (2.05)	25.65[b] (1.74)	40.34[a] (2.70)

[a,b] Different superscripts indicate statistical difference ($P < 0.05$) between systems 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 7. Global warming potential (1,000 kg of CO_2e, on a 100-yr timescale) for the 3 different systems considered per 1,000 kg of expected edible carcass weight

Material or activity	Standard	Free range	Organic
Feed + water	3.14	3.69	4.08
Electricity	0.16	0.15	0.17
Gas + oil	0.43	0.34	0.31
Housing + land	0.53	0.78	1.03
Manure + bedding	0.14	0.16	0.08
Breeder	0.35	0.33	0.25
Broiler	4.06	4.80	5.41
Total[1]	4.41^{b} (0.44)	5.13^{ab} (0.52)	5.66^{a} (0.62)

[a,b] Different superscripts indicate statistical difference ($P < 0.05$) between systems 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.

of land occupation compared with that of the other systems. In addition to higher feed consumption in the organic system, this was also caused by a higher land area requirement for the production of organic crops.

The breakdown of the environmental impacts by activity (breeders, broilers, Tables 6 to 10) shows that most of the burdens originated from the commercial broiler generation. For example, in the categories of primary energy use and GWP, the proportion of burdens associated with breeding birds is only 4 to 8%.

The results confirmed the general observation that broiler production has relatively low environmental impacts when compared with LCA studies for other meat products found in literature (Williams et al., 2006; de Vries and de Boer, 2010). They also demonstrate the high relative impact of feed production in the broiler industry (over 70% of total GWP), as for example, in beef production systems, the GWP related to feed was found to be <50% of the total (Williams et al., 2006). In the present study, the values for GWP were of the same magnitude as reported in earlier studies for broiler production (Williams et al., 2006; de Vries and de Boer, 2010), but the EP and AP were lower compared with those shown in an earlier study for 3 different UK broiler systems (Williams et al., 2006). Some of the differences between these studies were because of more up-to-date detailed data being made available for our research than was available to Williams et al. (2006). One specific reason for the differences is the fact that the estimated feed consumption in Williams et al. (2006) was higher than that observed in the present data, but the GWP per unit of feed was lower because some of the high-impact ingredients, such as fish meal and pure amino acids, were not included, and the land-use changes were not taken into account in Williams et al. (2006). The amount of feed consumption affected the amount of manure produced (and the amount of nutrients within), which affected the subsequent emissions from the housing and field. In contrast, the primary energy use in this study was estimated to be about twice as high as in Williams et al. (2006) This may have been caused by the inclusion of new ingredients into the diet, the production of which requires high energy consumption (fish meal, pure amino acids, and a higher proportion of soy), and also by the possible underestimation of farm energy consumption in the earlier study. However, it must be stressed that the results presented in the current study do not claim to be the average of all UK production systems. The data are broadly representative, but performance will

Table 8. Eutrophication potential (kg of PO_4 equivalent) for the 3 different systems considered per 1,000 kg of expected edible carcass weight

Material or activity	Standard	Free range	Organic
Feed + water	10.53	11.81	33.62
Electricity	0.00	0.00	0.00
Gas + oil	0.04	0.03	0.03
Housing + land	1.04	2.16	3.48
Manure + bedding	8.71	10.27	11.69
Breeder	1.67	1.61	1.16
Broiler	18.64	22.66	47.66
Total[1]	20.31^{b} (2.12)	24.26^{b} (2.51)	48.82^{a} (6.69)

[a,b] Different superscripts indicate statistical difference ($P < 0.05$) between systems only based 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 3 different systems considered per 1,000 kg of expected edible carcass weight

Material or activity	Standard	Free range	Organic
Feed + water	11.50	13.19	17.32
Electricity	0.55	0.49	0.57
Gas + oil	0.57	0.46	0.42
Housing + land	5.61	11.64	18.73
Manure + bedding	28.52	33.96	54.51
Breeder	3.30	3.17	2.30
Broiler	43.45	56.56	89.24
Total[1]	46.75^c (4.94)	59.73^b (6.11)	91.55^a (8.37)

[a–c]Different superscripts indicate statistical difference ($P < 0.05$) between systems only based 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 systems.

vary between producers with whatever system is in use. The farm activity data represented a limited number of years and 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. Furthermore, several assumptions related to model inputs increase the uncertainty of these inputs, and consequently, the uncertainty of the model outputs.

Some LCA studies for poultry production are also available from other countries, but in many cases the comparability with the current results is limited due to differences in methodology, including the selection of functional units, system boundaries, and impact categories. Katajajuuri et al. (2006), Katajajuuri (2008), and Usva et al. (2009) quantified the environmental impacts of broiler meat (functional unit 1,000 kg of marinated and sliced broiler fillet) in Finland and found GWP of 3,635 kg of CO_2e, which can be considered to be of similar magnitude as in this study. However, their estimates for EP and AP were considerably lower than those in the present study. Although there might be differences in farm and field emissions between studies, as suggested by de Vries and de Boer (2010), the actual reason for this discrepancy was the use of local characterization factors (Seppälä et al., 2004), which were specifically developed for Finnish conditions and differed strongly from the global factors used in most LCA studies.

Pelletier (2008) used LCA to predict the environmental impacts of the USA broiler industry. The values found for GWP, AP, and EP were considerably lower than those observed in the present study. The main reasons for the different GWP estimates between these 2 studies were the differences in the environmental burdens of the main feed ingredients and the differences in farm energy use. Furthermore, according to Pelletier (2008), the sources of EP and AP were almost entirely in feed production. This indicated very low emissions from housing and manure, which differed strongly from the results of the present study.

Boggia et al. (2010) compared the environmental impacts of 3 broiler production systems (conventional, organic, and organic-plus) in Italy. They presented the result of the impact assessment as normalized scores, in contrast to the absolute values applied in the present study, and therefore, most of these results are not directly comparable. However, one output variable that was common in both studies was the total CO_2 emissions. According to Boggia et al. (2010), this varied between 0.66 and 0.70 kg per 1 kg of broiler meat. Their values were very low and equal to about half of the total CO_2 emissions from only the feed production in the present study. This can be partly explained by lower feed consumption assumed by Boggia et al. (2010); for example, 2.0 kg per 1 kg of broiler meat. The rest of the difference must be caused by much lower environmental impacts of feed production in the study by Boggia et al. (2010) compared with that in the present study. It is not known which ingredients mainly caused this difference, but one explanation might be the use of domestic soy in Italy, as opposed to South American imported soy in the UK. Italian soy would not have any land-use change emissions and would have very low transport burdens compared with those from South American soy.

Ellingsen and Aanondsen (2006) assessed the environmental impacts of Norwegian fish production and

Table 10. Abiotic resource use, land occupation, and pesticide use for the 3 different systems considered per 1,000 kg of expected edible carcass weight

Burden	Standard	Free range	Organic
Abiotic resource use (kg of antimony equivalent)	18.9	22.3	34.0
Land occupation (ha)	0.56	0.72	2.50
Pesticide use (dose-ha)	2.77	3.46	0.29

compared these with chicken farming. In their study, the energy use per 0.2 kg of broiler fillet, including slaughtering and processing, was about 11 MJ, which is of similar magnitude as that in the present study. Other impact categories were presented in their study using only weighted, not absolute values, and therefore, direct comparison with the present study is not possible.

As the examples above demonstrate, although LCA studies are generally carried out according to international standards (BSI, 2006), the presentation of the results may differ considerably, and therefore, direct comparison between the studies is not always possible. This is understandable, given that the aim of LCA studies in many cases is to analyze differences between specific, well-defined systems, not to make comparisons with studies carried out elsewhere. Therefore, although there are existing studies on the environmental impacts of broiler production from various countries, it is not possible to make very strong conclusions about the differences in environmental friendliness of the systems between these countries. Furthermore, comparison between different studies is not feasible if the range of uncertainty in the results is not given. In fact, according to our knowledge, the present study is the first broiler LCA where a full uncertainty analysis has been carried out. The applications of uncertainty analysis in animal LCA are discussed in more detail in Leinonen et al. (2012).

Feed production and processing were the biggest of all material flow groups to affect the GWP. For many feed ingredients, especially those from the UK, it can be assumed that the crop production has occurred on mature agricultural land ($\geq$ 20 yr from the time of any land conversion; BSI, 2008). So, GHG emissions from land-use change (i.e., disturbing stored soil carbon and biomass) do not occur in significant quantities. However, some ingredients, most notably soy and palm oil, can potentially be considered to be produced on land that has only recently been converted from natural vegetation to agricultural use. This occurs mainly in South America and South Asia. In this study, a weighted average for soy was calculated based on the land-use change statistics, as described in the Materials and Methods section. However, there is not a full international agreement on the method of how to account for land-use changes in LCA. For example, an earlier version of carbon footprinting method PAS2050 (BSI, 2008) required that when the origin of an ingredient is not known, the worst case scenario should be assumed; that is, the origin should be entirely from land recently converted to agricultural use. We believe our approach to be more representative. On the other hand, it can be argued that any use of a certain crop, either from mature or new agricultural land, will increase its demand globally, and therefore, increases the pressure for land-use change (Audsley et al., 2009). This would require equal treatment of this crop in LCA, regardless of its actual origin. The selection among these methods is currently a much-debated topic, and it potentially has a very big effect on the estimate of the environmental impact of broiler feed and broiler production in general.

In addition to the general comparison of different broiler production systems, the modeling framework presented in this study provides an opportunity to carry out detailed farm level assessments on how to reduce the environmental impacts of production. Given that the analysis is largely based on functional relationships built in the animal and crop production submodels, it is possible to examine holistic impacts of possible changes in the system. For example, changes in consumption and composition of feed have impacts on both of the environmental impacts occurring during the crop production and the feed processing, and also on the subsequent emissions from poultry manure during housing, storing, and field application. Another example is the differences in the growth rate of broilers, which affect the amount of feed consumed per functional unit, the amount of manure produced, and the amount of energy and buildings needed, among other things.

Better environmental performance is becoming one of the targets of broiler breeding programs. The current results confirm the conclusions of Pelletier (2010), that improving feed efficiency, including the quantity, composition, and nutrient content of consumed feed has the potential to reduce the environmental impacts of broiler production. Initial studies to quantify these potential improvements have already been carried out (Jones et al., 2008) and the application of the modeling framework with functional relationships developed in the present study will allow even more detailed and realistic approaches in this area.

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APPENDIX 1

Details of Burdens and Potentials Used in the Current Study

The use of resources and emissions to the environment are collectively termed environmental burdens. Environmental impacts are a consequence of particular burdens. For example, nitrate leaching is a burden, and the consequent eutrophication is an impact. Emissions to the environment, whether from farms, industrial processes, or transport, are initially quantified by individual chemical species. Several of these are aggregated into environmentally functional groups:

Global Warming Potential. The global warming potential (GWP) can be calculated using timescales of 20, 100, or 500 years, of which the 100-year timescale is applied in the current study. The main source of GWP in the poultry industry is CO_2 from fossil fuel and land-use change together with small amounts of N_2O and CH_4. It is quantified in terms of CO_2 equivalent: 1 kg of CH_4 and 1 kg of N_2O are equivalent to 25 and 298 kg of CO_2, respectively, when a 100-year timescale is applied.

Eutrophication Potential. The eutrophication potential (EP) was calculated using the method of the Institute of Environmental Sciences at Leiden University, the Netherlands (http://www.leidenuniv.nl/interfac/cml/ssp/index.html). The main sources of EP are NO_3 and PO_4 leaching into water and NH_3 emissions into the air. It is quantified in terms of phosphate equivalents: 1 kg of NO_3-N and 1 kg of NH_3-N are equivalent to 0.44 and 0.43 kg of PO_4, respectively.

Acidification Potential. The acidification potential (AP) was calculated using the method of the Institute of Environmental Sciences at Leiden University, the Netherlands (http://www.leidenuniv.nl/interfac/cml/ssp/index.html). The main source of AP in the poultry industry is NH_3 emissions together with SO_2 from fossil fuel combustion. Despite being alkaline, ammonia contributes to acidification when deposited into soil or emitted into the atmosphere; it is oxidized to nitric acid. The AP is quantified in terms of SO_2 equivalents: 1 kg of NH_3-N is equivalent to 2.3 kg of SO_2.

Primary Energy Use. The energy use includes diesel (e.g., feed production and transport), electricity (e.g., ventilation), and gas (e.g., heating). These are all quantified in terms of the primary energy needed for extraction and supply of fuels, otherwise known as energy carriers. The primary fuels are coal, natural gas, oil, and uranium (nuclear electricity). They are quantified as MJ of primary energy, which varies from about 1.1 MJ of natural gas per MJ of available process energy to 3.6 MJ of primary energy per MJ of electricity. A proportion of electricity is produced by renewable sources, such as wind and hydro-power, which account for 3.6 and 8% of the United Kingdom and European electricity, respectively.

Land Occupation. Land occupation for producing crops for feed was calculated assuming average yields for grade 3a land (Bibby and Mackney, 1969). The land grading systems in the United Kingdom include 5 main grades (or classes) from 1 to 5 (with 6 and 7 in Scotland). Grade 1 is the best quality. Most arable production is on land of grades 2 to 3b, and 3a was selected as being closest to the typical, average-quality land. Yields were scaled up or down using linear coefficients derived from Moxey et al. (1995) for other land grades. A uniform yield was assumed for overseas crop production.

Abiotic Resource Use. The use of disparate abiotic resources can be aggregated by scaling them in relation to the scarcity of each resource. We applied the method of the Institute of Environmental Sciences at Leiden University, the Netherlands (http://www.leidenuniv.nl/interfac/cml/ssp/index.html). The scale is quantified in terms of the mass of the element antimony (Sb), which was an arbitrary choice. Their data includes metals, many minerals, and fossil fuels that tend to dominate in agriculture. For example, 1 kg of Fe, 1 kg of P, and 1 kg of crude oil are equivalent to 4×10^{-8}, 8×10^{-5}, and 2×10^{-2} kg of Sb, respectively.

APPENDIX 2

Table A1. Broiler breeder diet composition (%)

Item	Starter (0–6 wk)	Grower (6–15 wk)	Pre-layer (16–18 wk)	Breeder 1 (19–40 wk)	Breeder 2 (40–60 wk)
Raw material					
Wheat	61.42	59.17	65.40	68.00	69.62
Wheat feed	8.00	22.00	15.00	3.00	3.00
Sunflower	2.00	5.00	4.00	3.00	1.00
NGM[1] hipro soy	23.00	9.50	10.00	15.00	15.00
Vegetable oil blend	2.00	1.00	1.30	2.50	2.00
Soy oil	0.30				
Limestone	1.00	1.60	2.70	7.00	8.00
Mono-calcium phosphate	1.20	0.80	0.70	0.70	0.60
$NaHCO_3$	0.30	0.30	0.25	0.25	0.25
Salt	0.20	0.18	0.20	0.20	0.20
Lysine HCl	0.15	0.10	0.10		
DL-Methionine	0.15	0.10	0.10	0.10	0.08
L-Threonine					
Enzyme (NSP[2]/2×phytase)	0.03				
Breeder starter premix	0.25				
Breeder grower premix		0.25			
Breeder layer premix			0.25	0.25	0.25
Total	100.00	100.00	100.00	100.00	100.00
Nutrients and energy					
ME (MJ/kg)	11.95	11.30	11.60	11.60	11.50
CP	20.00	15.00	15.00	15.50	15.00
Lysine	1.05	0.72	0.70	0.69	0.68
Methionine	0.42	0.34	0.33	0.33	0.30
Methionine+cystine	0.77	0.64	0.62	0.62	0.59
Tryptophan	0.25	0.20	0.20	0.20	0.20
Threonine	0.67	0.51	0.50	0.53	0.51
Arginine	1.23	0.96	0.92	0.95	0.92
Valine	0.87	0.69	0.67	0.69	0.68
dig[3] lysine	0.93	0.63	0.61	0.61	0.60
dig methionine	0.40	0.31	0.30	0.31	0.28
dig methionine+cystine	0.69	0.56	0.55	0.56	0.53
dig tryptophan	0.22	0.17	0.17	0.18	0.17
dig threonine	0.57	0.43	0.42	0.45	0.44
dig arginine	1.11	0.84	0.81	0.89	0.83
dig valine	0.77	0.61	0.59	0.62	0.60
Ca	0.88	0.90	1.30	2.90	3.30
P	0.65	0.62	0.54	0.46	0.43
Available P	0.54	0.35	0.35	0.35	0.32
Na	0.19	0.16	0.15	0.15	0.15
Cl	0.22	0.20	0.21	0.20	0.20

[1] NGM = nongenetically modified.

[2] NSP = nonstarch polysaccharide.

[3] dig = digestible.

Table A2. Broiler breeder premix diet specifications (per 1 kg of premix)

Ingredient	Starter	Grower	Layer
A (IU)	11,000	10,000	10,000
D (IU)	5,000	3,500	5,000
E (IU)	60	40	100
K (mg)	3	3	5
B_1 (mg)	3	2	3
B_2 (mg)	6	5	12
B_6 (mg)	4	3	5
B_{12} (μg)	20	15	30
Folic (mg)	1.5	1.0	2.0
Calcium-D-pantothenate (mg)	15	15	15
Nicotinic (mg)	30	30	50
Biotin (mg)	0.2	0.2	0.3
Choline chloride (mg)	250	200	250
Fe (mg)	40	40	50
Cu (mg)	16	16	10
Mn (mg)	100	100	100
Zn (mg)	100	100	100
Cobalt (mg)	0.2	0.2	0.2
Iodine (mg)	1.25	1.25	2.00
Se (mg)	0.3	0.3	0.3

Table A3. Standard broiler diet composition (%)

Item	Starter (0–10 d)	Grower (11–24 d)	Finisher (25–32 d)	Withdrawal (33 d plus)
Raw material				
Wheat	60.12	58.97	56.23	56.46
Whole wheat		5.00	10.00	10.00
Rapeseed whole	4.50	5.00	8.00	8.00
NGM[1] hipro soy	25.20	23.00	19.00	19.00
Fishmeal	5.00	1.50		
Vegetable oil blend	0.70	2.00	3.00	3.00
Soy oil	1.50	1.50	1.00	1.00
Limestone	1.40	1.20	1.00	0.90
Mono-calcium phosphate	0.60	0.60	0.50	0.45
$NaHCO_3$	0.15	0.15	0.18	0.18
Salt	0.10	0.15	0.15	0.15
Lysine HCl	0.25	0.25	0.30	0.25
DL-Methionine	0.30	0.30	0.26	0.24
L-Threonine	0.10	0.10	0.10	0.09
Enzyme (NSP[2]/2×phytase)	0.03	0.03	0.03	0.03
Starter premix	0.25			
Grower premix		0.25		
Finisher premix			0.25	
Withdrawal premix				0.25
Total	100.20	100.00	100.00	100.00
Nutrients and energy				
ME (MJ/kg)	12.7	13.1	13.4	13.4
CP	22.8	20.0	18.5	18.0
Lysine	1.44	1.20	1.08	1.04
Methionine	0.67	0.60	0.51	0.49
Methionine+cystine	1.04	0.94	0.84	0.82
Tryptophan	0.30	0.26	0.23	0.23
Threonine	0.94	0.81	0.72	0.71
Arginine	1.42	1.24	1.09	1.09
Valine	1.05	0.90	0.80	0.80
dig[3] lysine	1.28	1.08	0.97	0.94
dig methionine	0.64	0.56	0.49	0.47
dig methionine+cystine	0.94	0.86	0.77	0.76
dig tryptophan	0.26	0.23	0.20	0.20
dig threonine	0.81	0.70	0.63	0.62
dig arginine	1.30	1.12	0.98	0.98
dig valine	0.91	0.79	0.70	0.70
Ca	1.00	0.90	0.80	0.75
P	0.55	0.49	0.44	0.43
Available P	0.47	0.42	0.36	0.35
Na	0.17	0.15	0.15	0.15
Cl	0.24	0.22	0.21	0.21

[1] NGM = nongenetically modified.

[2] NSP = nonstarch polysaccharide.

[3] dig = digestible.

Table A4. Free-range broiler diet composition (%)

Item	Starter (0–28 d)	Finisher (28–52 d)	Withdrawal (52–56 d)
Raw material			
Wheat	68.43	73.283	72.08
NGM[1] hipro soy	24.53	19.46	18.63
Full fat soy	1.50	2.00	2.00
Vegetable oil blend	0.59	2.10	4.54
Soy oil	1.00		
Limestone	1.55	1.14	1.00
Mono-calcium phosphate	0.96	0.73	0.64
$NaHCO_3$	0.37	0.33	0.35
Salt	0.08	0.20	0.18
Lysine HCl	0.25	0.20	0.10
DL-Methionine	0.35	0.20	0.15
L-Threonine	0.10	0.08	0.05
Enzyme (NSP[2]/2×phytase)	0.03	0.03	0.03
Starter premix	0.25		
Finisher premix		0.25	
Withdrawal premix			0.25
Total	100.00	100.00	100.00
Nutrients and energy			
ME (MJ/kg)	12.2	12.5	13.0
CP	20.0	18.0	17.0
Lysine	1.15	0.98	0.88
Methionine	0.62	0.44	0.39
Methionine+cystine	0.96	0.77	0.71
Tryptophan	0.26	0.23	0.22
Threonine	0.78	0.69	0.64
Arginine	1.23	1.09	1.06
Valine	0.87	0.79	0.77
dig[3] lysine	1.05	0.89	0.78
dig methionine	0.60	0.43	0.37
dig methionine+cystine	0.89	0.70	0.64
dig tryptophan	0.22	0.20	0.20
dig threonine	0.68	0.60	0.55
dig arginine	1.12	0.99	0.95
dig valine	0.77	0.70	0.68
Ca	1.05	0.86	0.81
P	0.54	0.47	0.44
Available P	0.47	0.41	0.38
Na	0.17	0.20	0.20
Cl	0.17	0.22	0.20

[1] NGM = nongenetically modified.

[2] NSP = nonstarch polysaccharide.

[3] dig = digestible.

Table A5. Organic broiler diet composition (%)

Item	Grower (0–35 d)	Finisher (35 d plus)
Raw material		
Organic wheat	55.58	69.19
Organic soy exp	18.50	11.00
Organic full fat soy	5.92	7.00
Organic sunflower	10.00	5.00
Potato protein	4.80	4.50
Organic soy oil	1.60	
Limestone	1.35	1.10
Mono-calcium phosphate	1.31	1.30
$NaHCO_3$	0.38	0.36
Salt	0.21	0.20
Betaine	0.10	0.10
Organic premix	0.25	0.25
Total	100.00	100.00
Nutrients and energy		
ME (MJ/kg)	12.50	12.40
CP	22.00	18.00
Lysine	1.15	0.95
Methionine	0.41	0.34
Methionine+cystine	0.82	0.72
Tryptophan	0.29	0.25
Threonine	0.87	0.73
Arginine	1.40	1.12
Valine	1.10	0.94
dig[1] lysine	1.01	0.83
dig methionine	0.33	0.28
dig methionine+cystine	0.65	0.57
dig tryptophan	0.23	0.20
dig threonine	0.75	0.63
dig arginine	1.23	0.99
dig valine	0.96	0.82
Ca	0.94	0.82
P	0.67	0.61
Available P	0.42	0.40
Na	0.20	0.19
Cl	0.20	1.90

[1] dig = digestible.

Table A6. Broiler premix specifications (per 1 kg of premix)

Ingredient	Starter	Grower	Finisher	Withdrawal
A (IU)	12,000	12,000	10,000	10,000
D (IU)	5,000	5,000	4,000	4,000
E (IU)	70	50	40	40
K (mg)	8	6	5	5
B_1 (mg)	3	3	2	2
B_2 (mg)	8	8	5	5
B_6 (mg)	4	4	2	2
B_{12} (μg)	20	20	13	13
Folic (mg)	2	2	1.5	1.5
Calcium-D-pantothenate (mg)	15	15	8	8
Nicotinic (mg)	60	55	40	40
Biotin (mg)	0.35	0.3	0.15	0.15
Choline chloride (mg)	250	250	200	200
Fe (mg)	40	30	30	30
Cu (mg)	18	17	15	15
Mn (mg)	100	90	75	75
Zn (mg)	90	90	70	70
Cobalt (mg)	0.2	0.2	0.2	0.2
Iodine (mg)	2	2	1.75	1.75
Se (mg)	0.3	0.3	0.3	0.3
Maxiban[1] (mg)	625	625		
Elancoban[1] (mg)			500	

[1] Maxiban and Elancoban (Elanco Animal Health, Greenfield, IN).