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A carbon footprint analysis of egg production and processing supply chains in the Midwestern United States

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A B S T R A C T

We conducted a carbon footprint analysis to quantify the scale and distribution of life cycle greenhouse gas (GHG) emissions in contemporary intensive egg production and processing supply chains (up to the breaker facility gate) in the Midwestern United States. Feed production and use in pullet and layer facilities was found to contribute the largest share of supply chain emissions. Further optimization of feed use efficiencies and sourcing least-environmental cost feed inputs are therefore key leverage points for reducing the GHG intensity of regional egg products. Of particular efficacy will be reducing the fraction of animal-derived materials used as inputs to poultry feeds and/or sourcing least-GHG intensive (i.e. poultry rather than ruminant) animal-derived feed inputs. Managing supply chains for nitrogen (N) use efficiency is also a key consideration – both in terms of sourcing N-efficient crop inputs, and selection of manure management strategies to minimize N losses. Breeding for N use efficiency may also be efficacious in this respect. In contrast, contributions from egg processing and breaking stages to overall emissions were small (1% and 2% of supply chain emissions, respectively). Although making relatively minor contributions to supply chain emissions, the high degree of variability in reported energy and other (non-feed) resources used between facilities for pullet and layer production along with egg processing and breaking stages also indicates opportunities for streamlining towards more efficient industry norms.

1. Introduction

It is widely recognized that anthropogenic greenhouse gas (GHG) emissions are altering global atmospheric composition and impacting climate stability (IPCC, 2007; Allison et al., 2009). It is also increasingly accepted that food production systems – in particular, animal husbandry systems – contribute a large share of anthropogenic emissions (Garnett, 2008; Weidema et al., 2008; Pelletier and Tyedmers, 2011a,b). As international and national governance regimes are implemented to curb GHG emissions, adaptation and change in global food systems will provide a critical leverage point in achieving emissions reduction targets. From a business perspective, food industry companies that act early to identify and minimize supply chain GHG emissions will likely be at a competitive advantage, and may also be rewarded in the marketplace for environmentally responsible behavior (Pelletier and Tyedmers, 2008).

Egg production is a major animal husbandry activity globally, and an important contributor to overall food production. In 2009, 5,349,100 tonnes of eggs were produced in the continental United States – accounting for 8.5% of global egg production volumes (FAOStat, 2012). At 16.2% of US egg production, Iowa was the leading egg producing state (NASS, 2009). Previously, researchers have reported life cycle assessment (LCA) or carbon footprint results for egg production in Sweden (Cederberg et al., 2009), the Netherlands (Mollenhorst et al., 2006; Dekker et al., 2011), the UK (Williams et al., 2006; Leinonen et al., 2012), Australia (Wiedemann and McGahan, 2011) and Canada (Vergé et al., 2009). In addition, Nguyen et al. (2012) used LCA to evaluate least-environmental cost feed sourcing options (not including animal-derived materials). The inclusion of processing and breaking stages for egg products have not been reported in peer-reviewed studies to date, nor have comparable studies for US-based egg production.

We report here a carbon footprint analysis of the scale and distribution of GHG emissions in egg production and processing supply chains in the Midwestern United States, including high and low-performing scenarios, based on industry-reported data. Our study employs ISO-14044 (ISO, 2006) life cycle assessment (LCA)

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methods (but for quantifying GHG emissions only), and Intergovernmental Panel on Climate Change (IPCC) GHG accounting protocols. The intention of this study is primarily to assist the US egg industry and egg producers and processors elsewhere in benchmarking and taking steps to mitigate the GHG emissions associated with their operations. It may also have applicability to future marketing of regional egg products or other client and consumer education initiatives.

2. Methods

2.1. Goal and scope

Using industry-supplied activity data, we characterized the carbon footprint of egg production and processing supply chains in Iowa and adjacent states, reporting emissions in terms of a relevant unit of analysis (functional unit) for each supply chain node (for example, kg CO_2-e per 1000 pullets or tonne of eggs produced). In total, our analysis directly represented approximately 55% of pullets and layers in Iowa, and 49% of all eggs produced in Iowa in 2009.

Data for the study were collected and refined via survey and email correspondence with company representatives. These data were used to develop ISO-compliant life cycle inventory (LCI) models of feed milling operations, pullet and layer facilities, and shell egg processing and breaking operations. In the absence of company-specific information for hatcheries, data were adopted from an earlier study of US broiler production systems (Pelletier, 2008). These models were subsequently used to quantify and evaluate supply chain GHG emissions for each supply chain node and in aggregate based on the GHG accounting protocols advanced by the Intergovernmental Panel on Climate Change (IPCC, 2006). Both production-weighted average data along with low and high-emissions scenarios representing the range of reported data for each supply chain node were employed and analyzed. Scenario modeling was also undertaken to assess the mitigation potential of sourcing alternative animal-derived feed inputs.

The system boundaries for this analysis included all direct and indirect inputs and emissions arising from: the agricultural and industrial production systems from which raw materials for feed inputs are derived; the processing of raw materials; the production of feeds; the production of chicks; farm-level material and energy use at pullet and layer facilities; shell egg processing and packaging; egg breaking and processing; and all transportation stages up to the processing facility gate (Fig. 1). This analysis did not include emissions associated with the production and maintenance of infrastructure such as machinery and buildings (these typically make trivial contributions to supply chain emissions, since they must be amortized against total production over their anticipated lifespan (years) – for example, see Ayer and Tyedmers 2009).

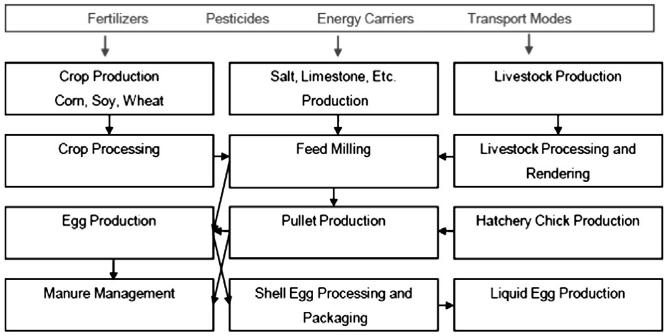

Fig. 1. System boundaries for assessing the carbon footprint of egg production and processing supply chains in the Midwestern United States.

2.2. Life cycle inventory

The life cycle inventory phase requires compiling inventory data representing the material and energy inputs, outputs and emissions at each stage of the supply chain of interest. Data for each supply chain node are expressed in terms of a relevant unit of analysis.

Data for the production and processing of agricultural and animal husbandry inputs for poultry feeds were taken from recent studies by Pelletier et al. (2010a,b) of beef and pork production supply chains in the Upper Midwestern United States, and global salmon aquaculture supply chains (Pelletier et al., 2009). Because these analyses applied the same modeling approach and assumptions, they could be directly adopted for use in the current analysis. Data for feed milling, pullet and layer facilities, and shell egg processing and breaking operations were supplied by participating companies. Background system data, including the production of primary energy carriers and transportation models, were derived from the EcoInvent (2010) database and modified, where appropriate, to most closely approximate regional conditions (i.e. by using US energy sources and mixes).

2.2.1. Agricultural feed ingredient models

Inventory data for wheat, soy and corn-based feed inputs are derived from US National Agricultural Statistics Service (NASS) publications, Iowa State University extension publications and peer-reviewed literature. Yields are based on 5-year averages for 2003–2007 calculated from NASS data. Application rates of pesticides and fertilizers used in soy and corn production are based on 2005 NASS data for Iowa. Inputs to wheat production represent US averages (see Pelletier et al., 2010a,b).

Average fertilizer mixes for nitrogen (N), phosphorus (P) and potassium (K) fertilizers were modeled using statistics provided by the International Fertilizer Industry Association. Inventory data for the production of individual fertilizers were derived from the EcoInvent database. These were representative of average European conditions but were modified to reflect regional energy mixes. All fertilizers and pesticides are assumed to be transported 1000 km (625 miles) by truck, and all seed inputs 100 km (62.5 miles) by truck. Energy inputs to crop production are based on Iowa averages (see Pelletier et al., 2010a,b).

Field-level ammonia, nitrous oxide, nitric oxide, nitrate and carbon dioxide (from urea fertilizers) emissions are calculated following IPCC (2006) Tier 1 protocols using relevant default emission factors. A 2.9% surplus phosphate emission rate is assumed following Dalgaard et al. (2008).

Processing of wheat, soy and corn applies inventory data reported by Pelletier et al. (2009, 2010a,b). Where electricity was required (for example, in crop drying) the US electricity mix was modeled based on International Energy Association data, including transmission losses.

Data for the production of ruminant, porcine and poultry byproduct meal and fat follow Pelletier et al. (2010a,b), Pelletier et al. (2009), Pelletier (2008), and Lopez et al. (2010).

2.2.2. Modeling N and P excretion and emissions (pullet and layer manure)

Nitrogen and phosphorus emission rates are calculated using a nutrient balance model based on feed composition and assuming that 2.2% of hen body mass is nitrogen and 0.6% is phosphorus, whereas eggs are assumed to contain 1.7% nitrogen and 0.21% phosphorus following Koelsch (2007). Nitrogen excretion estimates are used to calculate direct nitrous oxide, ammonia and nitric oxide emissions from manure management and indirect nitrous oxide emissions from nitrate leaching and ammonia emissions following IPCC (2006) protocols and relevant Tier I and Tier II emission factors

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at time of deposition, storage and application. Methane emissions from manure management are calculated following IPCC (2006) Tier I protocols. Phosphorus emissions are calculated at a 2.9% leaching rate at time of application of manure to agricultural lands following Dalgaard et al. (2008). Based on our survey results, the majority of poultry manure is applied to agricultural land locally within 10–14 km of the facilities (as is manure from the beef and pork supply chains previously modeled by Pelletier et al. in this region). The bulk of feed inputs are also regionally sourced (for example, corn, CDDGS, and soy are sourced from Iowa, and account for almost 80% of feed inputs). There are no imports of feed products from overseas. At the same time, the chemical fertilizer application rates for the crop models are based on USDA statistics, and do not include nutrient inputs from manure. For the purpose of our analysis, we hence consider manure to be recycled within the system (i.e. it is not accounted for as an input to crop production, nor are credits applied for avoided industrial fertilizer production when manure from pullet/layer houses is applied to agricultural land).

2.2.3. Co-product allocation

Co-product allocation is required to apportion resource use and emissions between the utilized products of multi-output systems. Since the purpose of the present analysis is to describe the biophysical environmental impacts of a food production system, we consider it most appropriate to base our allocation decisions on inherent biophysical characteristics of co-products which are relevant to the function provided by the product system. To this end, the gross chemical energy content of co-product streams was used as the basis for all allocation decisions because (1) producing caloric energy is the root driver of all food production activities (and energy provides an appropriate common denominator for fats, carbohydrates, and proteins) and (2) the chemical energy of food products present in raw materials is apportioned between processed outputs in a quantifiable manner which speaks directly to the ecological efficiency with which the system provides available food energy. This hence allows linking inputs and emissions in a logical, cause-effect manner. For a detailed discussion of this rationale, see Pelletier and Tyedmers (2011a,b, 2012). This approach was chosen over economic allocation, which has often been used in reported food system LCAs, because (1) economic allocation is a last-resort option in the ISO 14044 hierarchy and (2) the use of economic allocation typically produces results that poorly reflect the physical reality of the systems that are modeled. The use of substitution (following a consequential data modeling approach) was similarly deemed inappropriate for our analysis, which intends to establish a baseline rather than to model market-level consequences of possible changes in production systems.

2.3. Carbon footprint analysis and interpretation

A carbon footprint analysis involves calculating the contributions made by the material and energy inputs and outputs tabulated in the inventory phase to overall supply chain greenhouse gas emissions. All GHG emissions were calculated in terms of CO_2-equivalency over a 100-year time horizon according to IPCC (2006) protocols using the SimaPro 7.1 LCA software package from PRé Consultants. This assessment method follows the problem-oriented mid-point approach, meaning that results are expressed in terms of their potential environmental impacts (GHG emissions) rather than actual damage levels.

We first calculated GHG emissions per relevant unit of analysis (functional unit) for each supply chain node considered. We report both industry averages as well as low and high values for each supply chain node based on the range of inventory data recorded (here, production-weighted industry average inputs from upstream supply chain nodes are applied, whereas data points for average, worst and best performers are applied for the supply chain node of concern). Results are assessed to identify supply chain "hot spots" and opportunities for emissions reductions. Scenario modeling (not taking into account possible market-level effects) was also undertaken to assess the mitigation potential of alternative feed formulation strategies where ruminant by-product meal and fat are substituted with either porcine or poultry by-product meal and fat, or animal by-products are not used in feeds (here, we simply scaled the inclusion rates of agricultural inputs accordingly). In addition, to demonstrate the range of performance associated with least versus most-GHG intensive practices (not including potential changes in feed composition), we evaluate a whole supply chain scenario where either low or high-GHG emission practices are consistently achieved along the supply chain.

3. Results and discussion

3.1. Life cycle inventory results

Tables 1 and 2 and S1–S3 report the life cycle inventory data provided by participating companies (for inventory data for the production and processing of individual feed ingredients see Pelletier et al., 2009, 2010a,b) used to model and assess the supply-chain GHG emissions of regional egg production and processing systems in the Midwestern United States.

Reported energy inputs per tonne (1000 kg or 2200 lbs) of feed milled vary by almost an order of magnitude, from 12.7 to 84.8 MJ. Reported energy, water and feed use is similarly variable between pullet and layer facilities as well as shell egg processing and breaker plants – suggesting opportunities for streaming efficiencies towards an optimal common denominator. This high apparent variability, however, may also reflect differences in quality of data recording and reporting between facilities.

3.2. Carbon footprint analysis and interpretation of results

3.2.1. Feed inputs and feed milling

The cradle-to-mill gate GHG emissions characteristic of feed inputs sourced for pullet and layer feeds in Iowa in 2009 vary

Table 1
Life cycle inventory data for the production of 1000 pullets in ten reporting facilities in Iowa in 2009 (data represent the production of 16,205,643 pullets).

Input	Production-weighted average	Range
Chicks (#)	1031	1025–1047
Mass/chick (g)	39.8	39.1–40.0
Distance (km)	655	180–965
Feed (t)	5.27	5.05–5.75
Distance (km)	12.2	0–54.7
Water[a] (m^3)	9.22	8.85–10.1
Paper (kg)	4.00	0–8.63
Distance (km)	120	0–473
Energy (MJ)		
Electricity	2335	1716–3710
Diesel	214	0–1084
Gasoline	172	0–517
Propane	2287	0–4839
Fuel oil	11.8	0–158
Output		
Pullets (#)	1000	1000
Mass (kg)	1.23	1.13–1.30
Manure[b] (t)	2.35	0.74–4.16
Distance (km)	10.0	0–24.1
Estimated N loss (kg)	103	96.2–117
Estimated P loss (kg)	17.8	16.3–20.7

[a] Water use estimated as 1.75 × feed input.

[b] Manure mass on an as-removed basis (variable moisture content, depending on residency time, storage, and management strategies).

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Table 2
Life cycle inventory data per tonne of eggs produced in 13 reporting layer facilities in Iowa in 2009 (data represent 648,090,531 dozen eggs produced).

Input	Production-weighted average	Range
Pullets	37	15–47
Distance (km)	66.9	1.61–455
Layer feed (t)	2.25	2.06–2.50
Distance (km)	5.96	0–53.1
Water[a] (m^3)	3.98	3.32–5.39
Energy (MJ)		
Electricity	593	269–851
Diesel	41.3	0–158
Gasoline	3.89	0–33.8
Propane	154	0–635
LNG	13.5	0–287
Output		
Eggs (t)	1	1
Spent hens		
Mass (kg)	50	20–60
Distance (km)	100	100
Manure hauled[b] (kg)	1100	490–2110
Distance (km)	14.4	0–32.2
Estimated N loss (kg)	38.0	32.4–45.3
Estimated P loss (kg)	9.37	9.23–9.87
Mortalities		
Mass (kg)	5.72	1.08–11.0

[a] Includes water consumption by layers and other in-barn activities.

[b] Manure mass at time of removal (moisture content varies, depending on residency time and management strategy).

widely, from as low as 252 kg CO_2-e per tonne for soy meal to as high as 53,600 kg CO_2-e/tonne for ruminant fat. In general, the production of raw materials is the largest contributor to cradle-to-mill gate emissions, although processing-related emissions are notable for some inputs such as corn dried distillers grains with solubles (CDDGS) (Table S4). On average, raw material production accounts for 72% of emissions for feed inputs delivered to the mill gate, whereas processing contributes 16% and transportation 12%. For this reason, sourcing feed materials locally may potentially have a small influence in reducing supply chain emissions provided the materials have comparable production-related GHG emissions and feed conversion efficiencies are similar (Table S4).

Milling-related emissions from facility energy use also vary widely, but account for a very small fraction of emissions per tonne of feed produced. Notable here is that ruminant by-product meal and fat contribute a very large fraction of emissions (79%), despite their low inclusion rate (4.7%). This is unsurprising given the high levels of GHG emissions associated with ruminant production (Pelletier et al., 2010b). In contrast, corn accounts for 55% of feeds by mass but only 7.4% of associated emissions (Table 3). In general, the range of emissions characteristic of specific feed inputs underscores the importance of least-environmental cost feed sourcing as a key leverage point for reducing supply chain emissions (Pelletier et al., 2009, 2010a,b; Nguyen et al., 2012). For example, substituting ruminant by-product meal and fat with porcine or poultry-derived materials reduces emissions per tonne of feed by 66% and 69% respectively (Fig. 2). Removing animal by-products entirely reduces emissions by 79%. These results underscore the utility of employing physical as opposed to economic allocation criterion, since the latter would simply produce results reflecting market context rather than the physical reality of the underlying production processes. For example, in regulatory contexts penalizing the use of ruminant by-products due to BSE concerns, the relative price ratios may lead to LCA results suggesting that ruminant by-products have lower associated life cycle impacts than do poultry by-products (or even crop-based inputs) – which is absurd from a physical perspective given the much higher levels of material and energy inputs and associated emissions necessary to produce ruminants. Essentially, such an approach provides the signal that least-environmental cost feed sourcing simply requires purchasing the cheapest co-products, which we consider precisely contrary to the purpose of this analysis.

Table 3
Life cycle impact assessment of greenhouse gas emissions (kg CO_2-e/tonne of feed) for pullet/layer feed milling in Iowa in 2009.

	Average	% of total	Range[a]
Corn	142	7.41	141–143
CDDGS	51.2	2.67	50.6–51.8
Soy meal	37.8	1.97	36.8–38.4
Bakery material	20.4	1.06	20.4
Wheat middlings	18.1	0.94	16.8–18.6
Ruminant by-product meal	987	51.5	987–988
Ruminant fat	536	28.0	536–537
Corn germ	4.77	0.25	4.76–4.77
Limestone	2.73	0.14	1.91–3.11
Egg shells, shells, bone	<0.001	0	<0.001
Trace vitamins	0.001	0	0.001
Other	112	5.84	112
Feed milling	4.70	0.25	2.11–14.1
Total	1920		1910–1930

[a] Reflects differences in distances travelled for feed inputs as well as feed milling energy inputs only.

3.2.2. *Pullet facilities*

Per 1000 pullets produced, cradle-to-facility gate emissions range from 11,300–13,700, with a production-weighted average of 12,100 kg CO_2-e (Table S5, Fig. 3). This substantial range is largely a function of variable feed use efficiency between reporting facilities, since feed inputs contribute, on average, 83% of cradle-to-facility gate GHG emissions. Maximizing feed use efficiency and choosing low impact feed inputs the most important leverage points for reducing emissions at this supply chain node.

Emissions related to manure management (9%) are the second most important consideration. This includes small amounts of methane and, more critically, losses of nitrogen as gaseous compounds including ammonia and nitrous oxide (which has a global warming potential of 298 over a 100-year time horizon). Nitrogen losses may be reduced via improved feed use efficiencies, diet calibration, genetics programs for N-use efficiency, and manure management strategies which minimize N loss both at time of excretion and during storage and application.

Emissions related to in-barn energy use contribute, on average, only 6% of supply chain emissions but are highly variable between reporting facilities. Given the standardized nature of production in these facilities, it is possible that these large differences reflect uncertainties in data reporting rather than actual operational

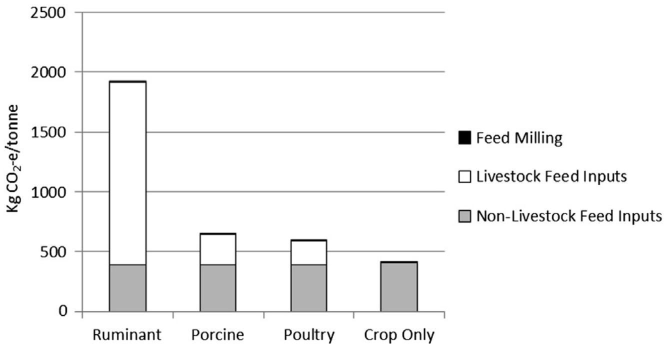

Fig. 2. Carbon footprint (kg CO_2-e/tonne of feed) for feeds milled in Iowa using ruminant, porcine, or poultry by-product meals and fats as inputs, or removing animal-derived materials altogether.

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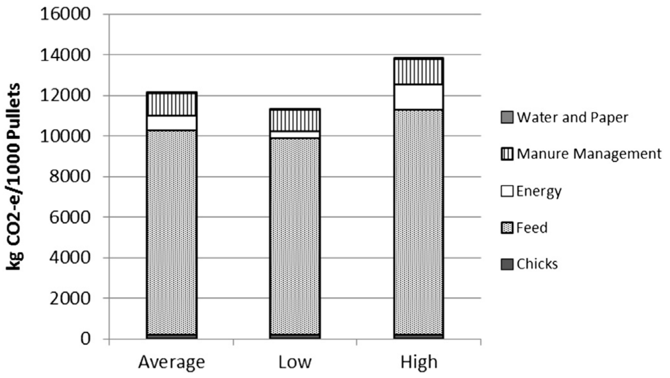

Fig. 3. Carbon footprint (kg CO_2-e) per 1000 pullets produced in pullet facilities in Iowa in 2009.

realities. Emissions related to chicks contribute only 1.6% of average emissions, and contributions from water and paper use are trivial.

3.2.3. Layer facilities

The range of total cradle-to-facility gate emissions per tonne of eggs produced is similarly large (4230–5990 kg CO_2-e), with a production-weighted average of 5020 kg CO_2-e/tonne (Table S6, Fig. 4). Again, GHG emissions from feed use are the primary determinant (82%). Manure-related emissions contribute, on average, 6.8%. This finding is in generally agreement with previously reported LCA research of egg production systems (Williams et al., 2006; Mollenhorst et al., 2006; Cederberg et al., 2009; Wiedemann and McGahan, 2011).

In contrast to chicks sourced for pullet facilities, inputs of pullets to layer facilities account for a larger share of cradle-to-facility gate emissions (8.5%). As with pullet production, emissions related to in-barn energy use (average of 2.8%) range widely, suggesting opportunities for improved efficiencies or possible anomalies in data tracking or reporting.

Given the central role of feed provision in determining overall emissions and the variable GHG intensity of feeds milled with different animal-derived inputs or with no animal-derived inputs, we also present estimates of supply chain emissions per tonne of eggs produced using the previously analyzed alternative feed formulations – assuming equivalent feed conversion efficiencies. Here, producing eggs when feed inputs at both pullet and layer facilities contain porcine in place of ruminant by-product meals and fat reduces supply chain emissions by 59%. When poultry by-products are used, emissions are reduced by 61%. When feeds containing no animal by-products are used (assuming equivalent feed conversion efficiencies), emissions are reduced by 70% (Fig. 5). Accordingly, depending on feed composition, the relative importance of feed as a determinant of supply chain emissions changes. Using ruminant by-products, layer feeds contribute 82% of cradle-to-facility gate emissions per tonne of eggs produced. This proportion shrinks to 56% when porcine materials are used, 53% when poultry materials are used, and 40% when only crop materials are used. Hence, if least-GHG intensive feeds are sourced, management interventions to improve other on-farm resource use efficiencies will play a proportionately more important role.

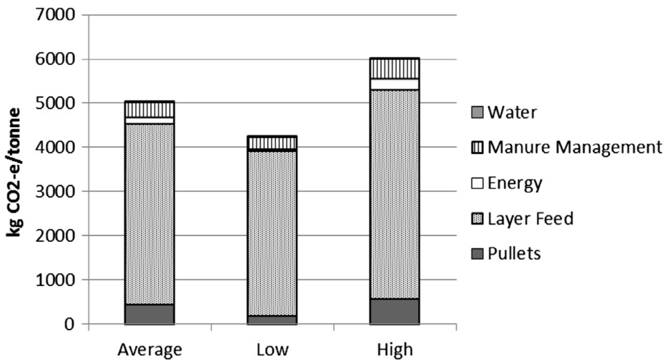

Fig. 4. Carbon footprint (kg CO_2-e/tonne) for the production of eggs in layer facilities in Iowa in 2009.

To put the GHG-intensity of Iowa egg production in perspective, we provide the following comparison: using similar methods, Pelletier et al. (2010a) recently estimated the GHG emissions per kg of pork production in this region at 3 kg CO_2-e/liveweight kg produced. For conventional, feedlot beef production, estimated emissions were 14.5 kg CO_2-e/kg liveweight production (Pelletier et al. 2010b). Both of these studies used methods identical to those employed in the current analysis, allowing for direct and robust comparability of results. Adapting the inventory data and methods of an earlier study of US broiler production (Pelletier, 2008) for methodological consistency with these analyses provides an estimate of 1.7 kg CO_2-e/liveweight kg of broiler poultry produced. Here, we estimated a GHG intensity of 5.0 kg CO_2-e per kg of eggs produced in Iowa (although this could potentially be reduced to 1.5 kg CO_2-e per kg using feeds not containing animal by-products).

Making a similar comparison on the basis of protein, the GHG intensity of Iowa egg protein production (raw, from whole eggs) is 45.4 CO_2-e/kg of protein compared to 11.5 kg CO_2-e/kg of broiler protein, 17.6 kg CO_2-e/kg for pig protein, and 78.4 kg CO_2-e/kg of beef protein.

Although differences in systems boundaries and other methodological considerations render comparisons with literature values published elsewhere problematic, it is nonetheless interesting to note that this value is considerably higher than the value of 1.3 kg CO_2-e/kg reported for egg production in Australia by Wiedemann and McGahan (2011), 1.4–2.0 kg CO_2-e/kg reported by Cederberg et al. (2009) for Sweden, higher also than the 3.9–4.6 kg CO_2-e/kg reported by Mollenhorst et al. (2006) for the Netherlands, but slightly lower than the value of 5.5 kg CO_2-e/kg reported by Williams et al. (2006). The low values for Australia and Sweden can, in part, be attributed to the use of rations not including animal-derived materials. Such differences also underscore the importance of context-appropriate allocation strategies, which do

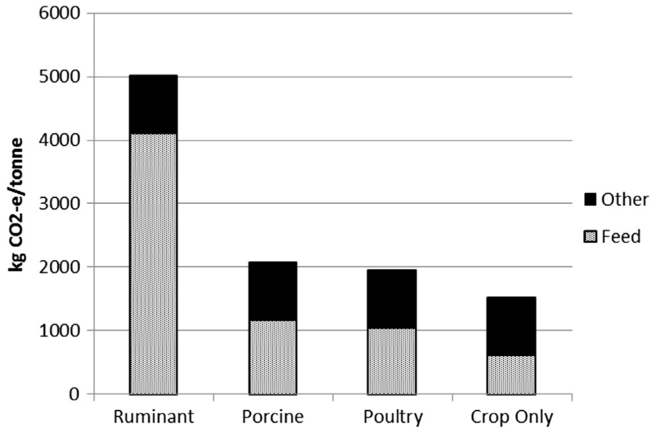

Fig. 5. Estimated cradle-to-facility gate carbon footprint (kg CO_2-e/tonne) for egg production in Iowa using feeds containing ruminant, porcine, or poultry by-products and fats, or no animal-derived inputs.

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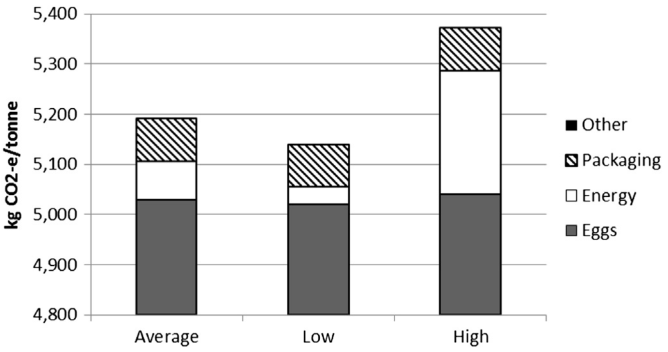

Fig. 6. Carbon footprint (kg CO_2-e/tonne) for processed, packaged eggs at shell egg processing facilities in Iowa in 2009 (note that scale begins at 4800). "Other" refers to water and mineral oil.

not produce results mirroring market context as opposed to the actual physical flows and emissions associated with the products in question.

3.2.4. Shell egg processing

GHG emissions per tonne of processed, packaged eggs are primarily determined by egg production (97%) (Table S7, Fig. 6). Emissions related to other inputs are variable. Excluding the production and transport of eggs, emissions for egg processing facilities at the low end of the observed range are 36% of those at the upper end, suggesting considerable opportunities for improved energy use efficiencies at this supply chain node. Energy-related emissions are highly variable, ranging from 34.8 to 247 kg CO_2-e per tonne of packaged product, reflecting both line efficiencies along with differences in energy sources. On average, however, energy-related emissions contribute only 1.5% of supply chain emissions. Emissions related to packaging are small but non-trivial (contributing an average of 1.6% of supply chain emissions). Contributions from water use are also variable but add negligibly to overall emissions.

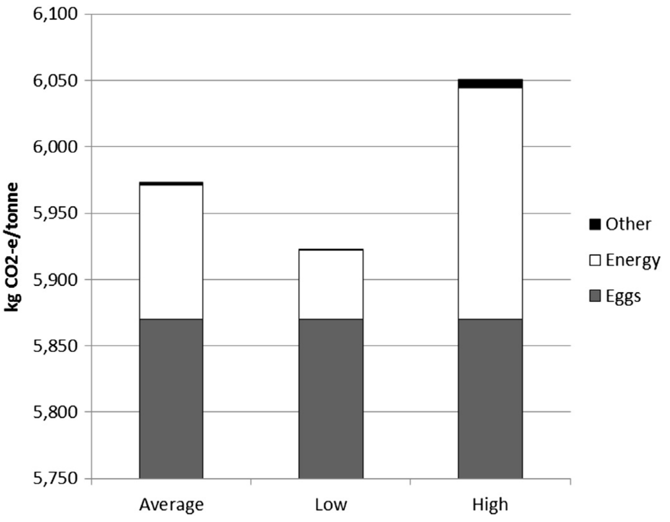

Fig. 7. Carbon footprint (kg CO_2-e/tonne) associated with the production of unpackaged, pasteurized, liquid whole egg at breaker facilities in Iowa in 2009 (note scale begins at 5750). "Other" refers to water and refrigerants.

Table 4
Production-weighted average versus hypothetical best- and worst-case scenario greenhouse gas emissions (kg CO_2-e) per functional unit produced along egg production and processing supply chains in Iowa in 2009 when inputs are sourced from facilities consistently demonstrating average, least, or most GHG-intensive practices respectively.

Supply chain node	Functional unit	Average	Low	High
Feed milling[a]	Tonne of feed	1920	1910	1930
Pullet facilities[a]	1000 pullets	12,100	11,200	13,800
Layer facilities[a]	Tonne of eggs	5020	4200	6100
Shell egg processor facilities	Tonne of eggs	5190	4320	6450
Breaker facilities	Tonne of liquid eggs	5980	4950	7480

[a] Reflects differences for performance variables other than feed composition.

3.2.5. Breaker facilities

For breaker facilities, eggs arriving at the facility gate accounted for, on average, 98% of overall supply chain emissions associated with production of unpackaged, pasteurized liquid eggs (Table S8, Fig. 7). Due to large differences in reported energy, water, and refrigerant use, associated facility-level emissions were similarly variable. For example, emissions related to facility energy use varied from as low as 51.8 kg CO_2-e per tonne of liquid eggs produced to as high as 174 kg CO_2-e. This difference suggests opportunities for improved energy use efficiency for participating breaker facilities, or possible data reporting anomalies. Emissions related to water and refrigerant use were trivial.

3.2.6. Hypothetical worst- and best-case supply chain scenarios

In light of the range of GHG emissions associated with reported practices at each supply chain node, it is also interesting to consider hypothetical best and worst-case scenarios relative to average industry performance. Towards this end, we analyzed two additional hypothetical supply chains where performance at each supply chain node reflected the best or worst of the range of reported activities for all inventory data points other than raw material production and feed composition (Table 4).

For feed production, differences between average, best and worst performing operations were trivial, largely because transportation and feed milling-related emissions contributed negligibly to total emissions (potential differences in raw material production and processing efficiencies were not considered). Continuing along the supply chain, however, these differences become much more apparent. For pullet facilities, the industry worst-case scenario, based on reported data, results in pullet production which is 23% more GHG-intensive than the best-case scenario. For layer facilities, the worst-case scenario results in egg production that is 45% more GHG intensive than the best-case scenario. For pullet and layer facilities, differences would be even more pronounced if company-specific feed compositions were modeled. For processed shell eggs, the difference is 49%, and for unpackaged, pasteurized liquid whole egg 51%. Clearly, adoption of least GHG-intensive practices throughout the industry could substantially reduce greenhouse gas emissions from this sector.

4. Conclusions and recommendations

Our carbon footprint analysis of the distribution and magnitude of GHG emissions for egg production and processing supply chains in the Midwestern United States for 2009 provides both a benchmark of current performance and a basis for future mitigation efforts. Several key insights emerge.

From a supply chain perspective, the key leverage point for emissions reduction is continued efforts to maximize feed use efficiencies, because feed production accounts for the largest share

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of emissions in egg production. Achieving feed use efficiencies comparable to the best performing facilities industry-wide would much reduce aggregate emissions.

However, any such efforts need necessarily be attentive to the GHG intensity of potential alternative feed inputs. Here, the concept of least-environmental cost feed sourcing is of particular relevance, and must include attention to primary production, processing, and transportation phases. It is recommended that similar biophysical accounting methods be applied to any potential alternative feed input supply chains to ensure methodological consistency and comparability with the present analysis. Our scenario analysis of the mitigation potential of replacing ruminant by-product meal and fat with equivalent porcine or poultry materials, or using no animal-derived materials, suggests substantial potential emissions reductions. This is unsurprising given the considerable resource and emissions intensities of producing livestock, in particular ruminants. Formulating feeds free of livestock materials would reduce emissions a large margin, provided similar feed conversion efficiencies were maintained. In such cases, the relative importance of feed as a determinant of supply chain emissions decreases, whereas managing for other facility-level resource use efficiencies (in particular, energy use), becomes correspondingly more important.

Managing feed supply chains for GHG mitigation must also take into consideration nitrogen use efficiencies. N losses from poultry manure are the second largest contributor to GHG emissions in both pullet and layer facilities, and the upstream impacts of N fertilizer production and use are a primary determinant of feed input GHG intensity. Feed formulation, breeding, and selecting manure management strategies for optimal N use efficiencies are therefore powerful tools in supply chain carbon footprint reduction. Here, we modeled N losses using nutrient balances and emissions factors derived from IPCC protocols. Given the margin of error associated with manure N sampling, we recommend using this modeling approach. This will also maximize inter- and intra-company and product comparability. However, we also suggest continued efforts to improve and standardize company-level manure-N sampling accuracy, in order to allow for differentiation between facilities and production strategies looking forward.

We further report that egg processing and breaking stages contribute trivial emissions compared to those associated with egg production. However, on a concluding, cautionary note: our inventory analysis indicates non-trivial variability in reported material and energy use in pullet, layer, shell egg processing, and breaker facilities. It is unclear whether this variability reflects operational realities or discrepancies in data reporting. In case of the former, this would indicate opportunities for streamlining production towards the most efficient common denominator. In the latter case, better tracking and reporting of the inventory data categories employed in this analysis will be essential to continuing quantifying and seeking to reduce supply chain GHG emissions moving forward. We therefore recommend employing the inventory data tables provided in this document and supplementary information file as a basis for future data collection and records.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2013.04.041.

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