Egg Industry Center

FINAL REPORT

A Comparative Assessment of the Environmental Footprint of the U.S. Egg Industry in 1960 and 2010

REPORT PREPARED BY

Egg Industry Center

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EXECUTIVE SUMMARY

Food systems have been identified as major contributors to environmental change at local, regional and global levels. Continuous progress towards more resource efficient and environmentally friendly food production norms are hence an important societal objective.

The U.S. egg industry has evolved considerably over recent decades by incorporating new technologies and husbandry practices to make more efficient use of finite resources such as land, water and energy. Progress has been made on many fronts, including animal genetics, nutrition, disease prevention, housing equipment and environmental control, and efficiency of feed production and use. Contemporary productivity would have been difficult to imagine 50 years ago. However, to date there has been no comprehensive assessment of the resource demand and environmental effects of these changes in production practices and efficiencies.

Life cycle assessment (LCA) is the most widely used tool for studying environmental performance in food systems from a supply chain perspective. LCA is an ISO (14044) standardized framework for characterizing the material and energy flows and emissions along product supply chains, and quantifying how these contribute to a variety of resource use, human health, and environmental impact potentials. In this study, we used ISO-compliant LCA to quantify the environmental performance of U.S. egg production in 2010 vs.1960.

Using industry-supplied activity data that were collected using anonymous surveys, this study first characterized the material and energy inputs and emissions associated with contemporary egg production supply chains in the United States. The system boundaries for this analysis included all cradle-to-facility gate 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; and farm-level material and energy use and emissions of pullet and layer facilities. The data collected directly represented 57.1 million pullets and 92.5 million laying hens, or 26% and 33% of the respective stock populations in the United States in 2010. Subsequently, a parallel model of U.S. egg production in 1960 was developed based on published literature sources and in consultation with industry experts for comparison with 2010 production conditions. The environmental footprint indicators used in this study were:

- **Acidifying emissions (acidification)** - Emissions such as NO_x, SO_2, and NH_3 or processes that cause decreased pH in an ecological system, expressed as SO_2 equivalent (SO_2-e).
- **Eutrophying emissions (eutrophication)** - The introduction of nitrogen or phosphorus containing compounds, to aquatic systems (e.g., causes increased growth of algae), expressed as PO_4equivalent (PO_4-e).
- **Global Warming Potential (GWP)** - A relative measure of how much heat a greenhouse gas (GHG) traps in the atmosphere, expressed in terms of CO_2 equivalent (CO_2-e). This analysis uses GWP and "GHG emissions" interchangeably.
- **Cumulative Energy Demand (CED)** - Direct and indirect energy needs for the production of a service or good, expressed in MegaJoules (MJ).

In developing the 2010 and 1960 models, the following changes in production performance of pullets and laying hens in the United States were observed over time.

Compared with 1960 pullets, 2010 pullets have:
- 30% lighter body weight at onset of lay (1.2 vs. 1.7 kg or 2.69 vs. 3.8 lb);
- 48% less feed use over pullet-rearing period (5.3 vs. 10.2 kg or 11.6 vs. 22.4 lb); and
- 70% lower mortality over pullet-rearing period (3.5% vs. 11.7%).

Similarly, compared with 1960 laying hens, 2010 laying hens have:
- 26% less daily feed use (9.03 vs. 12.23 kg/100 hens or 19.9 vs. 26.9 lb/100 hens);
- 27% higher hen-day egg production (75.3% vs. 59.2%);
- 42% better feed conversion (1.98 vs. 3.44 kg or lb of feed per kg or lb of egg);
- 57% lower mortality (6.7% vs. 15.8% per year); and
- 32% less direct water use per dozen eggs produced (4.5 vs. 3.1 L or 1.2 vs. 0.8 gal).

Using the models developed for egg production supply chains in 1960 and 2010, the analysis showed the following reductions in the environmental footprint per kg of eggs produced in the United States over the 50-year time interval considered:
- 65% lower acidifying emissions (70 vs. 200 g SO_2-e);
- 71% lower eutrophying emissions (20 vs. 70 g PO_4-e);
- 71% lower GHG emissions (2.1 vs. 7.2 kg CO_2-e); and
- 31% lower CED (12.3 vs. 17.7 MJ).

The total supply of 77.8 billion eggs produced in the United States in 2010 was 30% higher than the 59.8 billion eggs produced in 1960. However, the total environmental footprint for 2010, in million metric tonnes of emissions and in million MJ for CED, is:
- 54% lower for acidifying emissions (0.329 vs. 0.724 SO_2-e);
- 63% lower for eutrophying emissions (0.094 vs. 0.253 PO_4-e);
- 63% lower for GHG emissions (9.8 vs. 26.2 CO_2-e); and
- 10% lower for CED (57.9 vs. 64.1).

Further analysis found that using 1960 technologies to produce the amount of egg supply for 2010 would require the following additional resources: raising 27% (78 million) more hens, growing 72% (1.3 million acres or 0.53 million hectares, or 5.2 metric tonnes) more corn, and growing 72% (1.8 million acres or 0.73 million hectares, or 1.7 metric tonnes) more soybean. Demand for these additional resources would, in turn, translate into greater environmental impacts.

The analysis also identified areas for future improvement in the industry's environmental footprint. Feed efficiency, least-environmental cost feed sourcing, and manure management are the three primary factors that determine the environmental impacts of U.S. egg production. Efforts focused on further research and improvements in these areas will therefore aid in continual reduction of the environmental footprint of the U.S. egg industry over time.

INTRODUCTION

Food systems have been identified as major contributors to environmental change at local, regional and global levels (FAO 2006; Garnett 2008; Pelletier and Tyedmers 2011a). For example, it is estimated that food systems contribute 30% to anthropogenic (or man-made) greenhouse (GHG) emissions in the European Union (Tukker et al. 2006). Due to enhanced biological nitrogen fixation in agriculture and the production and use of nitrogen fertilizers, food production is also the primary source of reactive nitrogen mobilization, accounting for approximately 80% of anthropogenic fixation (Socolow 1999, Galloway et al. 2004, 2008). Moreover, the food sector is a key driver of biotic resource appropriation (Vitousek et al. 1986; Imhoff et al. 2004; Haberl et al. 2007) and consumes significant amounts of energy (Pimentel and Pimentel 1996; Pimentel et al. 2005). Given that total food production volumes are anticipated to almost double by 2050 (FAO 2006) to meet the demand of a growing and increasingly affluent population, how to meet these demands without severely compromising ecological integrity across scales continues to be a defining challenge for society (Pelletier et al. 2008; Pelletier and Tyedmers 2011a).

The development of technologically advanced food production, processing and distribution systems over the past 50 years has created both substantial productivity gains and environmental consequences, despite continuing increases in resource utilization efficiency. In recent decades, considerable research efforts have been invested in interpreting the material and energy dependencies and environmental impacts associated with diverse food production systems, including livestock systems.

Odum's pioneering work on the energetics of global food systems (Odum 1967) spawned a wealth of research regarding energy use in food production, much of which was led by American researcher David Pimentel (as summarized in Pimentel and Pimentel 1996). More recent work on food system energetics includes analyses of beef (Heitschmidt et al. 1996), conventional and organic dairy (Refsgaard et al. 1998), bread (Gronroos et al. 2006) and poultry production systems (Castellini et al. 2006).

Ecological footprint analyses have similarly been used as an indicator of biophysical sustainability in food systems, and have been applied to tomato, dairy and wine production (Wada 1993; Thomassen and de Boer 2005; Niccolucci et al. 2008), farms and cropland (van der Werf et al. 2007; Cuadra and Bjorklund 2008; Liu et al. 2008), several aquaculture products (Larsen et al. 1994; Kautsky et al. 1997), and to quantify the resource appropriation associated with different dietary patterns (White 2000; Gerbens-Leenes and Nonhebel 2002).

Life cycle assessment (LCA) has been the most widely used tool for studying environmental performance in food systems from a supply chain perspective. LCA is an ISO (14044) standardized framework for characterizing the material and energy flows and emissions along product supply chains, and quantifying how these contribute to a variety of resource use, human health, and environmental impact potentials.

Most published LCA studies have treated single product systems or made comparisons between production technologies. Published studies have investigated oil seed crops (Schmidt 2007; Pelletier et al. 2008; Dalgaard et al. 2008), dairy systems (Cederberg and Mattsson 2000; Hogass-Eide 2002; Casey and Holden 2005; Olesen et al. 2006; Thomassen and De Boer 2008; Arsenault et al. 2009); beef production (Nunez et al. 2005; Ogino et al. 2004, 2007; Casey and Holden 2006; Pelletier et al. 2010a), pork production (Nunez et al. 2005; Eriksson et al. 2005; Basset-Mens and van der Werf 2005; Pelletier et al. 2010b) and poultry production (Mollenhorst et al. 2006; Ellingsen and Aanondsen 2006; Williams et al. 2006; Pelletier 2008). Several studies of fisheries and aquaculture production systems have also been reported (Zeigler et al. 2003; Papatryphon et al. 2004; Hospido and Tyedmers 2005; Thrane 2006; Ellingsen and Aanondsen 2006; Mungkung et al. 2006; Pelletier and Tyedmers 2007; Gronroos et al. 2006; Ayer and Tyedmers 2009; Pelletier et al. 2009; Pelletier and Tyedmers 2010). What is clear from all of these studies is that the impacts of food production vary widely both within and between production technologies, as well as along different dimensions of environmental performance. Also clear is that mitigation strategies must be attentive to trade-offs across environmental domains and supply chain activities.

Agricultural production in the United States has advanced considerably over recent decades by incorporating new technologies to make more efficient use of finite resources such as land, water and energy. Egg production has followed the same trend, achieving productivity levels that would have been difficult to imagine half a century ago. However, to date there has been no comprehensive assessment of the resource demand and environmental effects of these changes in production practices and efficiencies. In this study, we applied ISO-compliant LCA methods to quantify the changes in environmental performance in the U.S. egg industry between 1960 and 2010 as a result of these changes in production efficiencies.

The specific objectives of the study were to:

- Develop models of U.S. egg production supply chains in 1960 and 2010 with regard to both foreground system variables (e.g. feed conversion efficiency, bird body weight, bird mortality rate, hen-day egg production, etc.) and background system variables (e.g. efficiencies of energy provision, fertilizer production, production of feed inputs, transport modes, etc.);
- Characterize supply chain environmental performance for the U.S. egg industry in 1960 and 2010 in terms of energy use, acidifying, eutrophying, and GHG emissions; and
- Quantify the production performance gains and reduction in environmental impacts associated with technological and husbandry advancements over this 50-year interval.

The results of the study are intended to provide the U.S. egg industry and other stakeholders with science-based information concerning the impact of technological advancements in egg production on resource efficiencies and environmental performance. The study also offers insight as to key leverage points for further mitigation of environmental impacts and conservation of natural resources.

METHODS

GOAL AND SCOPE

An industry-wide, anonymous survey was conducted to acquire the necessary data for characterizing production performance and modeling the environmental footprint of the contemporary U.S. egg supply chain. The collected data represented 57.1 million pullets and 92.5 million laying hens, accounting for 26% and 33% of the pullet and laying-hen populations, respectively. The system boundaries for this analysis included all cradle-to-facility gate 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; and farm-level material and energy use at pullet and layer facilities (Figure 1). In the absence of company-specific information for hatcheries, data were adopted from an earlier study of U.S. broiler production systems (Pelletier 2008). 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 in high production volume contexts, since they must be amortized against total production over their anticipated lifespan – for example, see Ayer and Tyedmers 2009).

Next a parallel model of U.S. egg production in 1960 was developed based on published literature sources and in consultation with industry experts. These parallel models were subsequently used to quantify and evaluate the environmental performance of each supply chain stage in terms of cumulative energy demand (CED), greenhouse gas (GHG), acidifying and eutrophying emissions in 1960 versus 2010.

LIFE CYCLE INVENTORY

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

The 2010 Model

Foreground system data refer to information unique to the product system of interest. Foreground system data for feed milling, pullet and layer facilities were collected via anonymous surveys from participating companies. As previously stated, the data collected represented 57.1 million pullets and 92.5 million laying hens – accounting for 26% of pullet stock and 33% of laying-hen stock in the United States in 2010.

Background system data refer to information regarding processes linked to the foreground system in the supply chain of interest, but shared with other supply chains. In the context of our analysis, this includes the provision of energy carriers, inputs to crop production and other feed input production and processing systems, and transportation modes.

Background system data, including the provision of energy carriers, fertilizers, pesticides, and transportation models, were derived from the EcoInvent (2010) database and modified to reflect U.S. energy inputs.

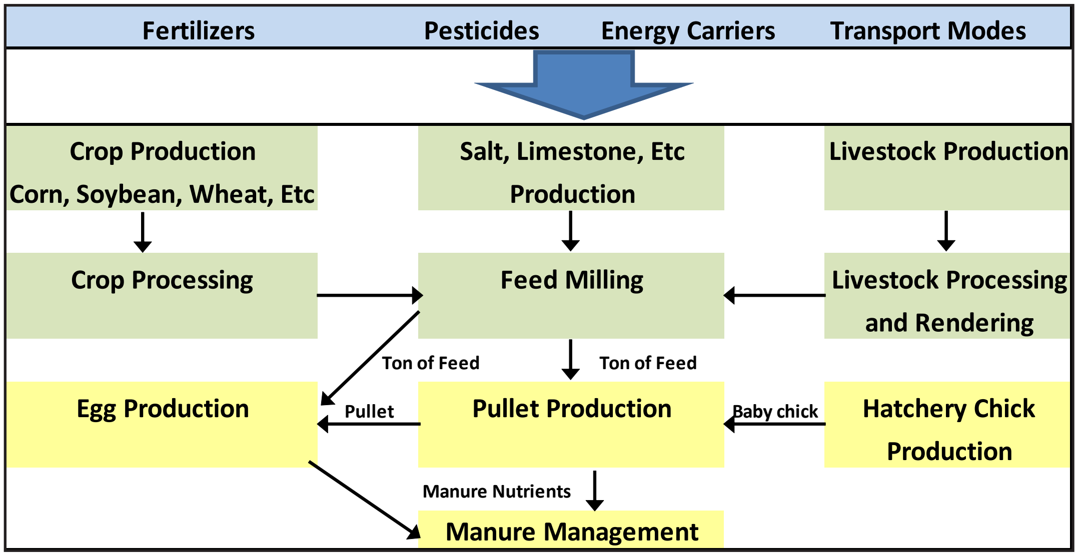


Figure 1. System boundaries for a life cycle assessment of egg production in the United States in 1960 and 2010 (background processes such as fertilizers, pesticides, and transport modes were derived from the EcoInvent (2010) database but were modified to reflect U.S. energy carriers).

Background system data for the production and processing of feed ingredients were adapted from recent LCA studies by Pelletier et al. (2010 a,b) of beef and pork production supply chains in the Upper Midwestern United States, and global salmon aquaculture supply chains (Pelletier et al. 2009). These studies used identical modeling parameters to those of the current analysis and hence the feed input models could be directly adopted.

Agricultural Feed Ingredient Models

Inventory data for wheat, soy and corn-based feed inputs were derived from U.S. National Agricultural Statistics Service (NASS) publications, Iowa State University Extension publications and peer-reviewed literature. Yields were based on 5-year averages for 2005-2010 calculated from NASS (2012) data. Fertilizer and pesticide mixes and application rates correspond to average U.S. consumption for each crop as reported by NASS (2012) and the International Fertilizer Association (IFA 2012). Energy inputs to cropping systems were also based on U.S. averages (NASS 2004). Field-level ammonia, nitrous oxide, nitric oxide, nitrate and carbon dioxide (from urea fertilizers) emissions were calculated following International Panel for Climate Change (IPCC) 2006 Tier 1 protocols using relevant default emission factors. A 2.9% surplus phosphate emission rate was assumed following Dalgaard et al. (2008). All fertilizers and pesticides were assumed to be transported 1000 km (625 miles) by truck, and all seed inputs 100 km (62.5 miles) by truck. Processing of wheat, soy and corn was based on inventory data reported by Pelletier et al. (2009; 2010 a,b). Data for the production of ruminant and porcine meat and bone meal and fat followed those in Pelletier et al. (2010 a,b) and Pelletier et al. (2009).

Modeling N and P Emissions

Nitrogen and phosphorus emission rates were 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 Koelsh (2007). Nitrogen excretion estimates were subsequently 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 at time of deposition, storage and application. Methane emissions from manure management were calculated following IPCC (2006) Tier I protocols. Phosphorus emissions were calculated at a 2.9% leaching rate at time of application of manure to agricultural lands following Dalgaard et al. (2008).

Co-product Allocation

Co-product allocation is required to apportion resource use and emissions between the products of multi-output systems. Since the purpose of the present analysis is to describe the cause-effect biophysical flows and associated environmental impacts of a food production system, it was deemed appropriate to base allocation decisions on an inherent biophysical characteristic of co-products which is also 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 (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. For a detailed discussion of this rationale, see Pelletier and Tyedmers (2011b). This approach was chosen over economic allocation, which is sometimes 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.

The 1960 Model

In developing a model to represent average U.S. egg supply chain characteristics in 1960, a variety of expert sources and published literature were used. This required estimating performance efficiencies for both foreground (e.g., egg production rate, feed conversion, bird mortalities) and background production system variables (e.g., provision of energy carriers, production of inputs to cropping systems, production of feed inputs, transportation modes, etc.). Where identification of a robust basis for characterizing specific foreground system variables for 1960 was not possible (e.g., energy use in poultry housing systems), 2010 data was used, but modified to accommodate the 1960s background system variables. This almost certainly resulted in an under-estimation of differences in the environmental performance of egg production in 1960 versus 2010.

1960 Energy Carriers

Energy return on energy invested (EROI) is a measure of the energy efficiency of energy production. Specifically, it is a dimensionless indicator of the amount of energy that is required to produce and bring to market an equivalent unit of a given energy carrier (for example, oil, gas, or electricity). Several researchers have reported declining EROI values for different energy carriers over time. As easily accessible, high-quality energy resources are exhausted, an increasing proportion of energy production derives from less-accessible, marginal energy resources that are more energy-intensive to exploit. In short, over time, more energy is required to produce an equivalent unit of energy. From a life cycle perspective, taking into account this changing efficiency and the associated changes in environmental burdens is essential to realistic, time-sensitive modeling.

EROI values at any given time differ between energy carriers, region of production, and production technology. Moreover, EROI can be described from both production and consumption perspectives. Since energy commodities are widely traded, calculating EROI values for energy carriers consumed in a given jurisdiction requires attention to trade patterns and, in the case of electricity, regionally-specific energy mixes.

For the purpose of the present analysis, EROI values for the United States as well as global EROI values for the production of specific energy carriers were adopted from or calculated based on the work of Lambert et al. (2012), Gangon and Hall (2009), Balogh et al. (in prep) and Guildford et al. (2011). In turn, these were used to calculate EROIs for primary energy carriers consumed in the United States in 1960 and 2010 based on U.S. Energy Information Adminstration (USEIA) 2012 statistics for U.S. consumption and imports of energy products. USEIA (2012) statistics for the energy mixes used in U.S. electricity production were also used to calculate 1960 and 2010 EROI values for electricity consumption (Table 1). On this basis, scaling factors were derived to represent the comparative EROI of energy carriers between 1960 and 2010. These factors were applied to modify the life cycle inventories used for 2010 energy carriers (adapted from the EcoInvent database) in order to arrive at 1960 energy carrier life cycle inventories which approximate changes in the environmental performance profile of energy carriers used in the United States over this interval. Potential differences in distribution losses for electricity (grid efficiencies) in 1960 compared to 2010 were not considered.

Table 1. Estimated EROI values for energy consumed in 1960 and 2010 in the United States.

ENERGY CARRIER	1960	2010	SCALING FACTOR BETWEEN 2010 AND 1960
COAL	75	60	0.8
OIL/GAS	47	15	0.3
NUCLEAR AND RENEWABLES	15	15	1.0
ELECTRICITY	14	14	1.0

1960 Fertilizer Production

U.S. fertilizer mixes for 1960 were derived from IFA statistics (IFA 2012). Ammonia production accounts for 87% of the fertilizer industry's energy consumption (IFA 2009). Based on data regarding improvements in the efficiency of ammonia plants over time, IFA (2009) shows that efficiencies improved from 58 to 28 MJ of energy required per tonne of ammonia produced between 1960 and 2010. Effectively, this means that producing ammonia in 1960 required 2.07 times as much direct energy input as in 2010. This ratio was applied in order to scale the energy inputs for average contemporary ammonia production for the EcoInvent database life cycle inventory used to represent contemporary ammonia production in order to arrive at a representative 1960 life cycle inventory. For all other fertilizer "building blocks," Kongshaug (1998) provides estimates of net energy consumption for "old technology - 1970", "average technology - 1998" and "best available technology - 1998." These estimates largely distinguish between net energy production in the form of steam, which may or may not be productively utilized. The modified EcoInvent processes for fertilizer production (originally representing average EU production, but modified to reflect U.S. energy inputs) used in the present analysis assume that net energy produced is lost as waste heat. For the purpose of this analysis, the same assumption was adopted. As a result, the difference between sulphuric acid, nitric acid and phosphoric acid net energy production in 1960 versus 2010 is not distinguished. However, the modified energy carrier inventories in the 1960 fertilizer production models were applied.

1960 Freight Transport

United States Department of Energy (USDE) data were used to calculate differences in the energy efficiency of freight transport by mode in 1960 compared to 2010 (USDE 2012). The energy intensity of U.S. heavy truck freight decreased from 24,960 BTU per vehicle mile in 1970 to 21,463 BTU per vehicle mile in 2010, with an average annual decrease of 0.4%. Making a linear extrapolation to 1960 on this basis, estimated energy intensity of road freight was 25,977 BTU per vehicle mile. A correction factor of 1.21 was therefore applied to the EcoInvent models used to represent U.S. road freight energy use in 2010 for the 1960 model.

The energy intensity of U.S. rail freight decreased from 691 BTU per ton-mile in 1970 to 289 BTU per ton-mile in 2010, with an average annual decrease of 2.2%. Making a linear extrapolation to 1960 on this basis, estimated energy intensity of U.S. rail freight was 859 BTU per ton-mile. A correction factor of 2.97 was therefore applied to the EcoInvent model used to represent U.S. rail freight energy use in 2010 for the 1960 model.

USDE (2012) only provides data for changes in the energy intensity of water freight on taxable waterways from 1997 (266 BTU per ton-mile) to 2010 (217 BTU per ton-mile), with an average annual decrease of 2.20%. Extrapolating back to 1960 suggests an energy intensity of 595 BTU per ton-mile in 1960, which would imply a correction factor of 2.74. This is very similar to the estimated correction factor for rail freight extrapolating from 1970-2010 time series data. This estimate is the weakest given that efficiency in 1960 is extrapolated from only 14 years of data spanning 1997-2010.

For comparison, using data from Fernley's Review for world seaborne trade from 1969-2010 (http://www.marisec.org/shipping-facts/worldtrade/volume-world-trade-sea.php) and estimates of marine fuel use from 1950-2010 (Eyring et al. 2005), the estimated correction factor for global ocean freight is 1.33. Elsewhere, based on a review of Lloyd's Register data, it has been suggested that the energy efficiency of ocean container freight has increased 35% between 1985 and 2008, suggesting an annual increase of 1.52% per year (http://www.worldshipping.org/benefits-of-liner-shipping/low-environmental-impact). However, for consistency with these calculations for road and rail freight, a correction factor of 2.74 was used.

1960 Feed Input Models

Smil et al. (1983) report energy inputs to U.S. corn production for 1959. On this basis, direct energy inputs were calculated to have declined 61% per unit production compared to reported energy inputs to corn production in 2001. This value, estimated by NASS (2004), was adopted for the 2010 model. No similar estimates were available to populate the 1960s model for soy and wheat. Instead, a proportionate decline in energy inputs relative to NASS (2004) energy use estimates for soybeans in 2002 and wheat in 1998 was assumed. Pesticide use for crops was based on statistics for 1964 provided by USDA (1995). Fertilizer use was also based on statistics for 1964 provided by USDA (2012). Sulphur and lime inputs were assumed to be similar between 1960 and 2010. Crop yield data for 1960 were taken from the USDA Feed Grains Database and USDA Oil Seeds Database.

All animal-derived and other feed inputs were based on the LCA models reported by Pelletier et al. (2009) (for fish meal) and Pelletier et al. (2010 a,b) (for porcine and ruminant materials). This was created using identical modeling protocols to those used for the 2010 model in the current analysis. For ruminant production, Pelletier et al.'s model for grass-fed beef production was used to represent 1960s conditions (versus their model of conventional, feedlot production to represent 2010 conditions). For porcine, Pelletier et al.'s model for low-performance niche production was used to approximate 1960s conditions (versus their model of conventional, commodity production to represent 2010 conditions). In the absence of an alternative model for boiler chicken production, it was assumed that spent layers destined for rendering were used for the production of poultry by-product meal and fat.

1960 Pullet and Layer Production

Animal husbandry performance data for pullet and layer production were taken from Winter and Funk (1960), and verified with industry experts. For pullets, this included: feed composition, feed consumed per pullet sold, mortality rate (% of initial placement), age, and body weight of pullets at the time of moving into the layer houses. For layers, this included: feed composition, feed consumption per day, egg production/layer/year, egg weight, feed conversion ratio, mortality rate, and number of pullets added to layer houses per year.

IMPACT ASSESSMENT AND INTERPRETATION

Impact assessment in LCA involves calculating the contributions made by the material and energy inputs and outputs tabulated in the inventory phase to a specified suite of environmental impact categories. In this study, cumulative energy use, GHG, acidifying and eutrophying emissions were quantified.

Energy use (MJ) was quantified following the Cumulative Energy Demand (CED) method (Frischnect et al. 2003), which accounts for conversion efficiencies and the quality of energy inputs. Global warming (CO2-equivalency over a 100-year time horizon according to IPCC 2006), acidification (SO2-equivalency), and eutrophication (PO4-equivalency) potentials were quantified according to the CML 2 Baseline 2000 method (Guinee et al. 2001). These assessment methods follow the problem-oriented midpoint approach, meaning that results are expressed in terms of their potential environmental impacts (as measured in resources used or emissions to the environment) rather than actual damage levels.

The environmental impacts were first assessed for each supply chain stage considered, and for supply chains in aggregate. Results for the 1960 and 2010 models were subsequently compared in order to determine differences in production efficiencies and environmental performance over time.

Also, a more detailed contribution analyses was conducted in order to determine the extent to which observed differences in environmental performance between egg production in 1960 and 2010 were attributable to different factors or model assumptions. The first such analysis evaluated the influence of differences in back-ground system variables between 1960 and 2010 only (i.e., production efficiencies for energy carriers, fertilizers, transport modes, and feed inputs). All 1960 sub-models were replaced with 2010 models for these parameters. The second analysis used the same feed composition as 2010 in the 1960 model, and replaced all 1960s background system sub-models with 2010 models in order to determine the differences strictly attributable to changes in either feed composition or animal husbandry practices and performance over time.

> Declining EROI values require energy carriers to be used more efficiently throughout the production chain just to compensate for the higher amount of energy needed to extract the carriers.

RESULTS AND DISCUSSION

LIFE CYCLE INVENTORY RESULTS

The life cycle inventory data used for the 2010 and 1960 models of U.S. egg production supply chains are presented in Tables 2-9. Inventory data for production and processing of individual feed ingredients (other than corn, wheat and soy) are not provided herein but can be found in Pelletier et al. (2009, 2010a,b).

Substantial increases in crop yield over the 50-year interval, in many cases, offset increases in inputs used for production depending on the input and crop (Table 2). For feed milling, the reported proportions and total amounts of different energy carrier inputs per tonne of feed milled were highly variable (Table 3), as were the distances travelled for the feed inputs sourced (Table 4). For the purpose of our analysis, we applied total consumption-weighted averages to arrive at the proportions and feed transport distances we modeled.

Reported data were similarly variable for pullet and layer facilities for parameters such as water use, energy use, manure mass, etc. Again, although the ranges are reported in the following tables, production-weighted averages were used to construct the life cycle inventory model.

Substantial increases in crop yields, in many cases, offset increases in inputs used for production.

Table 2. Life cycle inventory data per tonne (1000 kg or 2200 lb) of corn, soy and wheat produced in 1960 and 2010. For other feed input life cycle inventory data, see Pelletier et al. (2009, 2010a,b).

	2010			1960		
INPUTS	CORN	SOY	WHEAT	CORN	SOY	WHEAT
FERTILIZER (KG)						
N	16.1	1.12	20.1	16.6	0.74	9.17
P_2O_5	5.55	5.53	6.91	10.8	2.72	7.03
K_2O	5.71	7.75	1.36	8.50	3.35	3.93
SULPHUR	**0.27**	**0.13**	**0.53**	**0.27**	**0.13**	**0.53**
LIME	**33.5**	**0.00**	**0.00**	**33.4**	**0.00**	**0.00**
ENERGY						
DIESEL (L)	4.49	10.9	13.2	4.47	17.5	21.3
GAS (L)	1.17	3.49	3.02	12.1	5.62	4.86
LPG (L)	7.02	0.00	3.82	2.68	0.00	6.16
ELECT. (KWH)	4.33	0.00	11.9	0.00	0.00	19.19
TOTAL PESTICIDES (KG)	**0.25**	**0.46**	**0.29**	**0.20**	**0.21**	**0.12**
HERBICIDES	0.24	0.45	0.12	0.13	0.09	0.11
INSECTICIDES	0.01	0.01	0.00	0.08	0.11	0.01
OTHER (FUNGICIDES)	0.00	0.00	0.17	0.00	0.00	0.00
SEED (KG)	**2.10**	**23.4**	**34.5**	**20.5**	**45.0**	**41.8**
OUTPUTS						
NITROUS OXIDE (KG)	**0.46**	**0.25**	**0.55**	**0.49**	**0.27**	**0.36**
AMMONIA (KG)	**2.38**	**2.19**	**4.13**	**3.57**	**3.91**	**4.46**
NITRIC OXIDE (KG)	**0.35**	**0.02**	**0.43**	**0.36**	**0.02**	**0.20**
CARBON DIOXIDE (KG)	**17.2**	**0.17**	**3.04**	**14.3**	**0.03**	**0.42**
NITRATE (KG)	**1.44**	**0.00**	**0.00**	**4.49**	**0.00**	**0.00**
PHOSPHATE (KG)	**0.00**	**0.00**	**0.03**	**0.14**	**0.00**	**0.00**
YIELD (TONNE)	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table 3. Energy inputs per tonne (1000 kg or 2200 lb) of pullet/layer feed milled in reporting facilities in the United States in 2010 (representing a total production of 2,679,405 tonnes of feed). This dataset was also used for the 1960 model.

	PRODUCTION-WEIGHTED AVERAGE	RANGE
ELECTRICITY (MJ)	15.8	1.8-52.9
DIESEL (MJ)	51.1	0-122.8
GASOLINE (MJ)	1.5	0-3.4
NATURAL GAS (MJ)	0	0-0.02

Table 4. Distances travelled for inputs to pullet/layer feed milled in reporting facilities in the United States in 2010 (representing a total production of 2,679,405 tonnes). This dataset was also used for the 1960 model.

FEED INPUT	DISTANCE TO PROCESSOR[1] (KM)	DISTANCE TO FEED MILL[2] (KM)	RANGE
CORN	-	27	24-48
CORN DRIED DISTILLERS GRAINS WITH SOLUBLES (CDDGS)	25	116	1-193
SOY MEAL	100	96	29-133
BAKERY MATERIAL	WHEAT: 100 TO FLOUR MILL, FLOUR: 1000 TO BAKERY	258	97-587
WHEAT MIDDLINGS	100	474	241-604
MEAT AND BONE MEAL	100	151	56-322
FAT	100	272	0-579
SALT	25	370	0-861
LIMESTONE	100	142	0-241
CALCIUM	100	186	137-225
PHOSPHATE	100	239	0-861
TRACE VITAMINS	100	325	0-563

(1) Assumed average distances

(2) Production-weighted average

Both the types and inclusion rate (%) of ingredients in pullet and layer feeds have changed between 1960 and 2010 (Tables 5 and 6). While corn and soy products constitute the core bulk ingredients for both periods considered, wheat was a more important input in 1960 than in contemporary egg production. Several ingredients also figure in only one period or the other – for example, green feed and fish meal in 1960 pullet feeds, and bakery material in 2010 pullet and layer feeds. Notable here is the reduced fraction of animal-derived materials (roughly 40% of 1960 levels) in contemporary feeds. The nitrogen and phosphorus percentages in different feed ingredients, as used to estimate the nutrient balance, are listed in Table 7.

Table 5. Pullet feed composition for egg production in the United States in 1960 (based on Winter and Funk 1960) and 2010 (based on the production-weighted average of feed composition data from the reporting pullet producers).

	1960	2010	2010
	% INCLUSION	% INCLUSION	RANGE
CORN	78.1	60.0	41.0-70.7
CORN DRIED DISTILLERS GRAINS WITH SOLUBLES (CDDGS)	1.0	6.2	0-13.0
SOY MEAL	10.3	21.0	13.0-27.0
DEHYDRATED GREEN FEED[1]	3.0	0.0	N/A
FISH MEAL	1.2	0.0	N/A
BAKERY MATERIAL	0.0	1.0	0-13.0
WHEAT MIDDLINGS	0.0	0.9	0-7.0
MEAT AND BONE MEAL[2]	2.5	1.0	0-5.7
FAT[3]	0.3	0.9	0-1.7
SALT	0.5	0.3	0-0.4
LIMESTONE	1.5	6.2	0-10.5
DICALCIUM PHOSPHATE	0.6	0.0	N/A
CALCIUM	0.0	1.3	0-10.0
PHOSPHATE	0.0	0.7	0-1.5
OTHER[4]	1.0	0.5	0-2.1

(1) Modeled as alfalfa hay based on Pelletier et al. (2010a)
(2) 63% ruminant, 26% porcine, 11% poultry (assumed same as 2010)
(3) 50% poultry, 50% vegetable (assumed to be soy oil) (assumed same as 2010)
(4) Includes trace vitamins and minerals, modeled as DL-methionine

Table 6. Layer feed composition for egg production in the United States in 1960 (based on Winter and Funk 1960) and in 2010 (based on feed composition data from the reporting egg producers).

	1960	2010	2010
	% INCLUSION	% INCLUSION	RANGE
CORN	63.9	58.6	40.5-69.2
CORN DRIED DISTILLERS GRAINS WITH SOLUBLES (CDDGS)	0	6.1	0-15.1
SOY MEAL	12	19.3	10.0-25.7
BAKERY MATERIAL	-	0.9	0-12.4
WHEAT MIDDLINGS	10	0.8	0-9.9
DEHYDRATED GREEN FEED[1]	2.5	0	N/A
MEAT AND BONE MEAL[2]	5	1.8	0-7.8
FAT[3]	1	0.9	0-4.4
SALT	0.5	0.3	0-1.0
LIMESTONE	3.7	6.8	0-11.6
DICALCIUM PHOSPHATE	1.3	0	N/A
CALCIUM	0	2.1	0-9.8
PHOSPHATE	0	0.5	0-1.0
OTHER[4]	0.1	0.5	0-1.8

(1) Modeled as alfalfa hay
(2) 81% ruminant, 17% porcine, 2% poultry
(3) 4% ruminant, 2% porcine, 58.5% poultry, 35.5% vegetable (assumed to be soy oil)
(4) Includes trace vitamins and minerals, modeled as DL-methionine

Table 7. Proximate composition of feed inputs used for calculating intake, excretion and losses of N and P.

FEED INGREDIENTS	% N	% P
CORN	1.224	0.260
CORN DRIED DISTILLERS GRAINS WITH SOLUBLES (CDDGS)	4.224	0.710
SOYBEAN MEAL	6.899	0.620
BAKERY BY-PRODUCT	1.728	0.250
WHEAT MIDDLINGS	2.706	0.910
ALFALFA HAY (17% CP)	2.720	0.250
MEAT AND BONE MEAL	8.000	4.000
FISH MEAL (66% CP)	10.56	3.150
FAT	0	0
LIMESTONE	0	0.020
PHOSPHATE	0	0.4364
TRACE VITAMINS	0	0
METHIONINE	8.750	0

Perhaps most striking at the inventory level are the differences in resources consumed and other performance parameters for pullets (Table 8) and layers (Table 9) production in 1960 compared to 2010. Feed consumption per pullet decreased by 48% over the 50-year interval considered, in part explained by a 30% lower body weight at the onset of production (which requires less feed) and in part by a 70% lower mortality rate (Table 8). As a result of reduced mortality, the number of chicks required (per thousand pullets produced) has also decreased by a net 8.6% (Table 8). At the same time, estimated losses of N and P have decreased by 39% and 60%, respectively. Unfortunately data for energy inputs to pullet facilities in 1960 were not availble; hence, it was assumed to be comparable to energy used in 2010.

Pullet mortaility rate decreased by 70% and feed consumption per pullet grown decreased 48%.

Table 8. Life cycle inventory data for the production of 1000 pullets in the United States in 1960 (based on Winter and Funk 1960) and in 2010 (based on the production-weighted average data from the reporting pullet producers representing 57,116,182 pullets).

	1960	2010	2010	PERCENT
INPUTS	AVERAGE	AVERAGE	RANGE	CHANGE
CHICKS	**1133**	**1036**	**1021-1047**	**-9%**
MASS/CHICK (G)	39.8	39.8	39.1-40.0	0%
DISTANCE (KM)	434	434	32.2-845	0%
FEED (KG)	**10.2**	**5.27**	**4.31-5.75**	**-48%**
DISTANCE (KM)	19.2	19.2	0-112	0%
WATER[1] (M^3)	**17.9**	**9.22**	**7.54-10.1**	**-48%**
ENERGY[2] (MJ)				
ELECTRICITY	3015	3015	1425-5721	0%
DIESEL	105	105	0-1084	0%
GASOLINE	95.8	95.8	0-517	0%
PROPANE	1654	1654	0-4747	0%
NATURAL GAS	187	187	0-1932	0%
FUEL OIL	2.63	2.63	0-158	0%
OUTPUTS				
PULLETS	**1000**	**1000**	**1000**	**0%**
MASS (TONNE)	1.74	1.22	1.16-1.30	-30%
MANURE[3] (TONNE)	**6.46**	**3.38**	**0.59-4.59**	**-48%**
DISTANCE[4] (KM)	10.0	10.0	10.0	0%
ESTIMATED N LOSS (KG)	178	108	81.9-122	-39%
ESTIMATED P LOSS (KG)	32.9	13.3	9.09-15.7	-60%
BODY WEIGHT (KG/BIRD)	**1.7**	**1.2**	**1.16-1.30**	**-30%**
MORTALITY RATE (%)	**11.7**	**3.5**	**2.1-4.7**	**-70%**

(1) Water use estimated as 1.75 x feed input.
(2) Year 1960 data assumed to be same as 2010.
(3) Manure mass on an as-removed basis, assuming proportionate to the ratio of feed use to manure production in 2010.
(4) Assumed distance of travel from farm to destination of manure application.

Table 9. Life cycle inventory data per tonne of eggs produced in the United States in 1960 (based on Winter and Funk 1960) and in 2010 (based on the production-weighted average data from the reporting egg producers representing 1,542,507.6 tonnes of eggs).

	1960	2010	2010	PERCENT
INPUTS	AVERAGE	AVERAGE	RANGE	CHANGE
PULLETS	**46**	**36**	**21-50**	**-22%**
DISTANCE (KM)	52.9	52.9	1.61-452	0%
LAYER FEED				
KG/100 LAYERS/DAY	12.23	9.03	8.1-11.3	-26%
KG OF FEED/KG OF EGGS	3.44	1.98	1.76-2.32	-42%
DISTANCE (KM)	12.6	12.6	0-53.1	0%
WATER (M^3)	**6.25**	**4.26**	**3.06-6.58**	**-32%**
ENERGY[1] (MJ)				
ELECTRICITY	557	557	335-1030	0%
DIESEL	69	69	0-318	0%
GASOLINE	9	9	0-34.0	0%
NATURAL GAS	4	4	0-102	0%
LPG	81	81	0-634	0%
OUTPUTS				
EGG PRODUCTION	**1**	**1**	**1**	**0%**
EGGS/100 LAYERS/DAY)	59.18	75.34	68.8-81.1	27%
EGGS/LAYER/YEAR	216	275	251-296	27%
MASS/EGG (G)	60.5	60.0	54-63	-1%
SPENT HENS[2]				
MASS (KG)	64.4	50	32.0-70.0	-22%
DISTANCE (KM)	100	100	100	0%
MANURE HAULED[3] (KG)	**1980**	**1140**	**510-2350**	**-42%**
DISTANCE[4] (KM)	14.4	14.4	0-32.2	0%
ESTIMATED N LOSS (KG)	61.7	32.4	32.4-45.3	-47%
ESTIMATED P LOSS (KG)	16.1	5.78	9.23-9.87	-64%
MORTALITIES[5]				
RATE (% PER YEAR)	15.8	6.7	1.2-8.4	-57%
MASS (KG)	11.6	5.47	1.10-11.0	-53%

(1) Year 1960 data assumed same as 2010.
(2) 34.5% to human consumption, 4.5% to pet food, 49.4% to rendering, 6.2% to composting, 5.0% to "other."
(3) Manure mass at time of removal. Moisture content varies, depending on residency time and management strategy.
(4) Estimated distance for removed mass.
(5) Includes culls. 60.3% to rendering, 25.2% to composting, 0.5% to burial, 2.1% to landfill, 11.8% to incineration (assuming no energy recovery).

For egg production, the lower bird body weight (2.0 kg or 4.5 lb/layer in 1960 vs. 1.5 kg or 3.4 lb/layer in 2010) is one of the main drivers for the 26% lower feed consumption per hen in 2010 (Table 9). The lower daily feed use, combined with a 27% higher hen-day egg production and a 57% lower mortality rate, results in 42% less feed consumed per kg of egg produced. The number of pullets sourced per tonne of eggs produced has decreased by 22% (Table 9) because of lower mortality. Nitrogen and phosphorus emissions have decreased by 47% and 64%, respectively.

Substantial increases in pullet and laying hen production performance and crop yields led to a significant reduction in resources use per kg of egg produced.

LIFE CYCLE IMPACT ASSESSMENT AND INTERPRETATION OF RESULTS

Life Cycle Impact Assessment Results for Energy Carriers in 1960 versus 2010

Energy return on energy invested (EROI) was substantially higher (i.e., 35%-65%) in 1960 for all primary energy carriers other than coal (Figure 2). The low EROI for coal in 1960 is explained by the low energy costs of extracting coal relative to the energy costs of transporting coal to markets. Since rail and water freight transport modes were considerably less energy efficient in 1960, the end result is a lower overall EROI for coal in 1960 compared to 2010. Emissions for electricity production are also slightly higher in 1960 compared to 2010, largely due to two factors. First is the higher fraction of (in particular) coal and other fossil fuels in the 1960 energy mix compared to a greater share of nuclear power generation in 2010. Second is the lower efficiencies of transforming primary energy carriers into electricity in 1960.

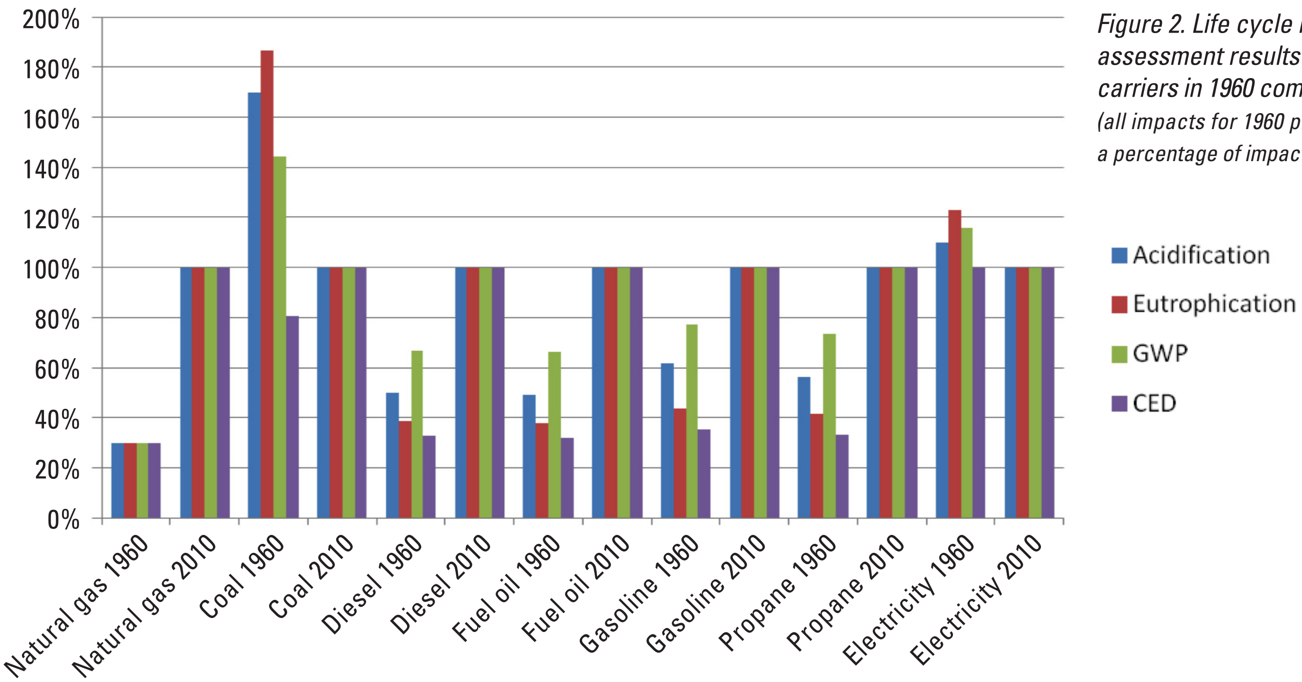
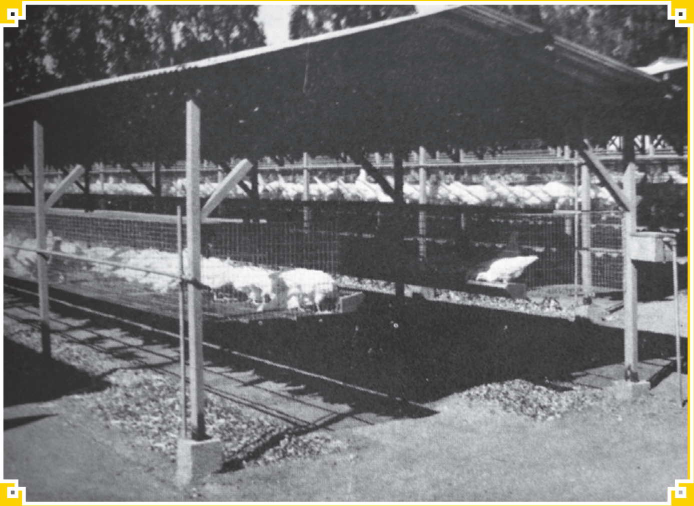


Figure 2. Life cycle impact assessment results for energy carriers in 1960 compared to 2010 (all impacts for 1960 presented as a percentage of impacts in 2010).



1960 Egg Production Facility

From "Keeping Chickens In Cages" (Hartman, 1957. 69)

2010 Egg Production Facility

Interior view of modern laying hen house

Life Cycle Impact Assessment Results for Fertilizer Inputs in 1960 versus 2010

Despite the substantial increases in the energy efficiency of ammonia production, declining EROI values for energy production effectively offset these gains. As a result, the comparative impacts of nitrogen fertilizers consumed in the United States in 1960 are very similar for 2010. Impacts for phosphorus fertilizer are also similar, with the exception of considerably higher eutrophication impacts in 1960, largely due to the larger fraction of triple super phosphate in the 1960 fertilizer mix. In contrast, all impacts associated with the U.S. potassium fertilizer mix were substantially higher in 1960 compared to 2010 due to the predominance of more energy-intensive K sources in 1960 versus greater reliance on less energy-intensive potassium chloride in 2010 (Figure 3).

Life Cycle Impact Assessment Results for Transport Modes in 1960 versus 2010

Acidifying, eutrophying, and GHG emissions per tonne-km of freight transport were considerably higher (>250%) in 1960 compared to 2010 for both rail and ocean freight. Interestingly, the declining EROI of fossil fuels over this interval offset almost exactly the improved fuel efficiencies enjoyed by contemporary fleets, resulting in very similar Cumulative Energy Demand (CED). For road freight, in contrast, CED was much lower in 1960, and all other impacts very similar to those estimated for 2010. This outcome reflects the lower efficiency gains for road freight compared to rail and ocean freight for the 50-year interval considered (Figure 4).

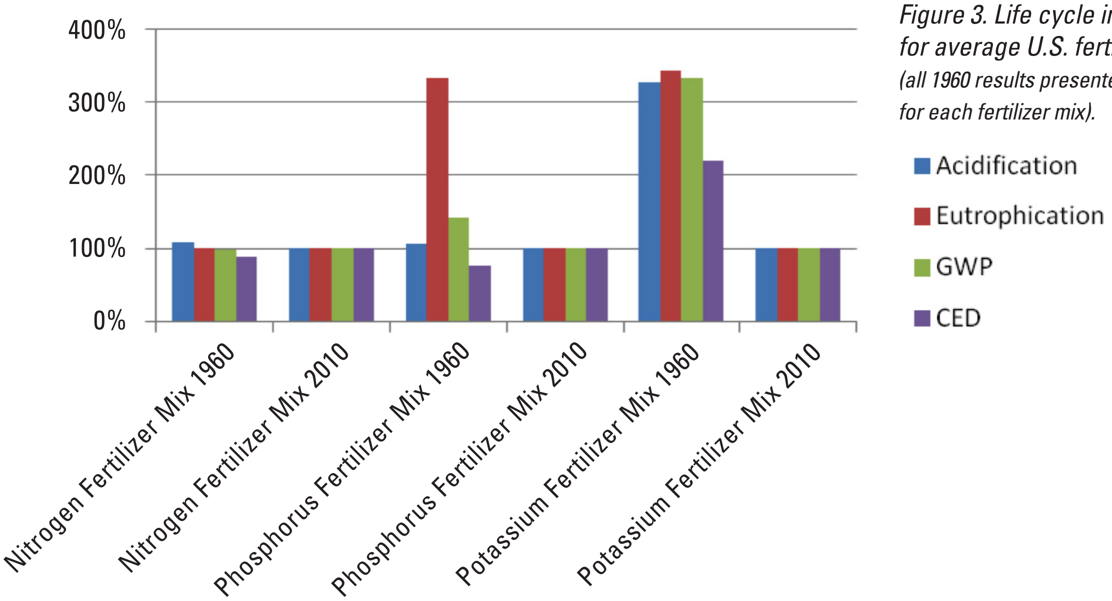


Figure 3. Life cycle impact assessment results for average U.S. fertilizer mixes in 1960 versus 2010 (all 1960 results presented as a percentage of 2010 results for each fertilizer mix).

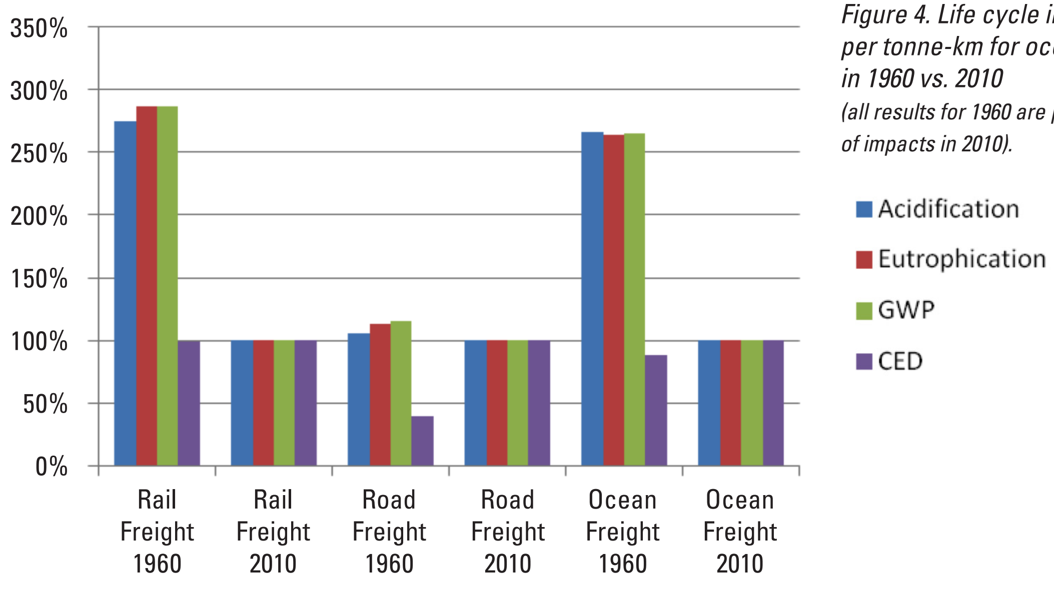


Figure 4. Life cycle impact assessment results per tonne-km for ocean, rail and road freight in 1960 vs. 2010 (all results for 1960 are presented as a percentage of impacts in 2010).

Life Cycle Impact Assessment Results for Feed Inputs in 1960 versus 2010

In general, the production of raw materials is the largest contributor to cradle-to-mill gate impacts for feed inputs to pullet and layer systems; however, processing-related emissions are notable for some inputs such as corn dried distillers grains with solubles (CDDGS). Milling-related impacts account for a very small fraction of emissions per tonne of feed produced. Production of animal-derived feed inputs is most impactful across impact categories. This is particularly true for the production of meat and bone meal and fat from ruminant sources compared to porcine and poultry sources, because feed inputs and associated emissions to produce ruminants are considerably higher.

Emissions-related impacts for feed inputs produced in 1960 are almost universally higher than those in 2010. This reflects a combination of factors, including improved efficiencies of nitrogen fertilizer production, transport modes and, in particular, much-improved yields in 2010. The opposite is true for CED, however, where declining EROI effectively outweighs other efficiency gains (Table 10).

Table 10. Life cycle impact assessment results per tonne of feed inputs at the farm or processor gate in 1960 and 2010 (Acidification in kg SO_2-e, Eutrophication in kg PO_4-e, Global Warming Potential in kg CO_2-e, and Cumulative Energy Demand in MJ).

FEED INGREDIENTS	YEAR	ACIDIFICATION	EUTROPHICATION	GWP	CED
CORN	1960	7	2	345	1380
	2010	5	1	301	1759
CDDG	1960	10	2	764	4425
	2010	7	1	719	7949
SOY MEAL	1960	7	1	249	1337
	2010	4	1	227	2601
SOY OIL	1960	15	3	541	2909
	2010	9	2	493	5621
BAKERY MATERIAL	1960	-	-	-	-
	2010	8	2	551	8736
WHEAT MIDDLINGS	1960	10	2	430	2364
	2010	10	.2	490	4222
ALFALFA HAY	1960	2	1	101	499
	2010	-	-	-	-
FISH MEAL	1960	6	3	714	4620
	2010	-	-	-	-
POULTRY M&B MEAL	1960	191	71	6472	31165
	2010	121	45	4605	42437
PORCINE M&B MEAL	1960	200	74	5820	20800
	2010	96	27	4318	24221
RUMINANT M&B MEAL	1960	565	254	34100	59600
	2010	404	185	25636	74133
POULTRY FAT	1960	331	124	11210	53980
	2010	209	79	7975	73457
PORCINE FAT	1960	400	149	11600	41500
	2010	193	54	8627	48306
RUMINANT FAT	1960	1136	511	68468	119788
	2010	812	371	51546	148951
SALT	1960	2	0	300	2543
	2010	2	0	263	3936
LIMESTONE	1960	0	0	47	779
	2010	0	0	43	964
CALCIUM PHOSPHATE	1960	39	1	1094	9328
	2010	38	1	938	15188

As a result of both, the differences in impacts attributable to feed inputs in 1960 compared to 2010, as well as changes in feed formulation over time (in particular, decreased use of animal-derived meals and oils), a similar pattern is observed for pullet and layer feeds. Averaged across emission-related impact categories, impacts for feeds in 2010 are 51% of those in 1960 for pullet feeds, and 37% for layer feeds per tonne of feed produced. In contrast, CED is 36% and 2% higher, respectively (Table 11).

Table 11. Life cycle impact assessment results per tonne of pullet and layer feeds produced in 1960 and 2010 (Acidification in kg SO_2-e, Eutrophication in kg PO_4-e, Global Warming Potential in kg CO_2-e, and Cumulative Energy Demand in MJ).

FEED & YEAR	ACIDIFICATION	EUTROPHICATION	GWP	CED
PULLET FEED 1960	18.4	6.8	1015	3139
PULLET FEED 2010	9.8	2.9	584	4267
LAYER FEED 1960	34.5	13.8	1860	4560
LAYER FEED 2010	12.5	4.4	782	4632

COMPARING PULLET PRODUCTION IN 1960 AND 2010

Emissions-related impacts of pullet production in both 1960 and 2010 are largely driven by two factors – feed inputs and manure management (Figures 5 and 6). For CED, direct energy inputs to pullet houses figure alongside feed inputs as a major contributor. However, the relative importance of these factors differ between 1960 and 2010. In 1960, feed inputs weighed most heavily across impact categories – in particular for GWP and CED. In 2010, manure management is the most important variable for acidifying and eutrophying emissions due to decreased emissions associated with the production of feed inputs. The importance of direct energy inputs has also increased in 2010, again due to the declining relevance of feed inputs as a result of changing feed composition (less animal-derived materials, which are particularly energy-intensive to produce).

Averaged across emissions-related impact categories, pullet production in 2010 has 44% of the impacts estimated for 1960. Cumulative energy demand is also slightly lower, at 91% (Table 12).

Table 12. Life cycle impacts assessment results for 1000 pullets produced in 1960 and 2010 in the United States.

YEAR	ACIDIFYING EMISSIONS (KG SO_2-E)	EUTROPHYING EMISSIONS (KG PO_4-E)	GHG EMISSIONS (KG CO_2-E)	CED (MJ)
1960	390	129	13458	45
2010	196	54	5404	41
REDUCTION, %	50	58	60	9

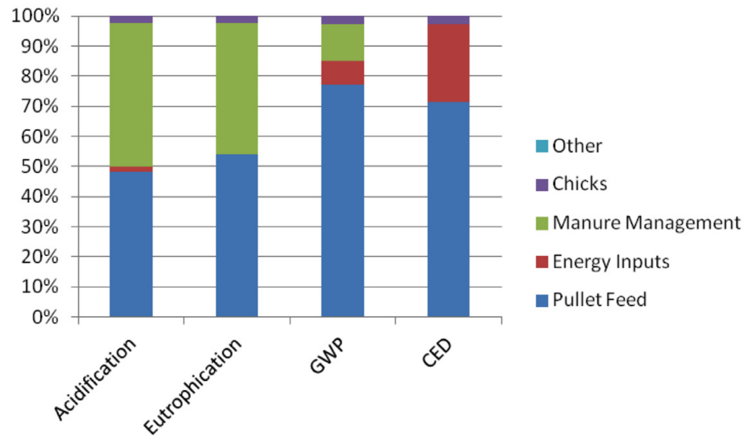


Figure 5. Contribution analysis for the life cycle impact assessment of pullets produced in the United States in 1960.

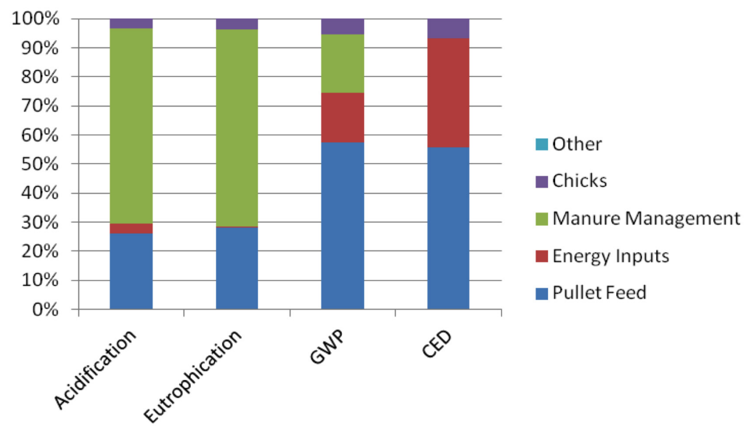


Figure 6. Contribution analysis for the life cycle impact assessment of pullets produced in the United States in 2010.

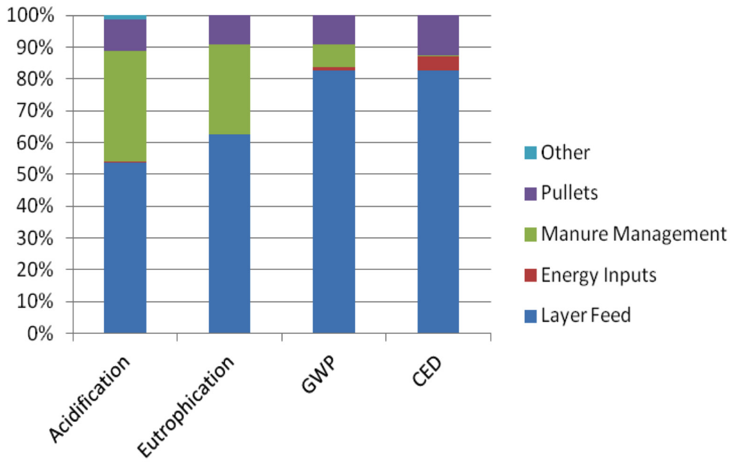


Figure 7. Contribution analysis for the life cycle impact assessment of eggs produced in the United States in 1960.

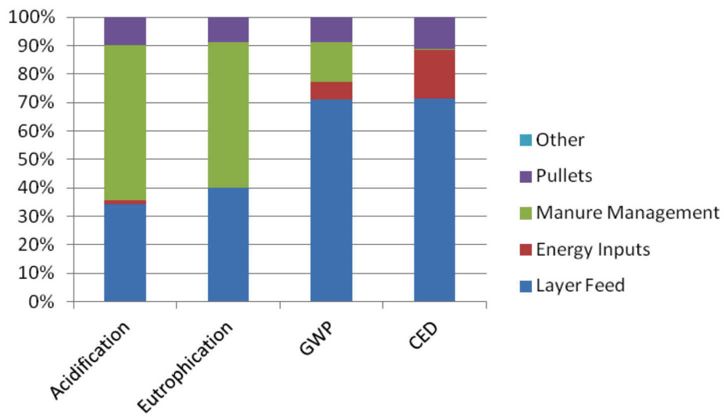


Figure 8. Contribution analysis for the life cycle impact assessment of eggs produced in the United States in 2010.

Feed efficiency, feed formulation and manure management are identified as the hotspots for further reduction in the environmental footprint of egg production.

COMPARING EGG PRODUCTION IN 1960 AND 2010

The distribution of impacts for egg production is very similar to that of pullet production for both 1960 and 2010 – in particular with respect to the changing importance of feed inputs and manure management. In 2010, manure management replaces feed inputs as the largest source of acidifying and eutrophying emissions (despite substantially lower losses of N and P per kg of eggs produced), whereas feed remains the dominant (although smaller) contributor to both GWP and CED. These changes are reflective of both changing feed composition and improved feed conversion efficiencies. Poultry production contributes roughly 10% to emissions-related impacts in both 1960 and 2010, and slightly more for CED (Figures 7-8). In general, direct energy inputs are of lesser importance. Overall, emissions-related impacts of egg production in 2010 are estimated to be 31% of those of 1960, while CED is 69% (Table 13).

Table 13. Life cycle impacts assessment results for one kg of eggs produced in 1960 and 2010 in the United States, and % reduction in impacts over the 50-year interval considered (Acidifying emissions in g SO_2-e, Eutrophying emissions in g PO_4-e, GHG emissions in g CO_2-e, and Cumulative Energy Demand in MJ).

YEAR	ACIDIFYING EMISSIONS	EUTROPHYING EMISSIONS	GHG EMISSIONS	CED
1960	200	70	7230	17.7
2010	70	20	2080	12.3
REDUCTION, %	65	71	71	31

Clearly, the U.S. egg sector has made significant strides in improving resource use efficiency and reducing environmental impacts per unit production since the 1960s. It is also interesting, however, to consider the extent to which such improvements mitigate impacts when considered in terms of changes in the scale of production. The total U.S. table egg production in 1960 was 59.8 billion eggs compared to 77.8 billion in 2010 (USDA NASS) – an increase of roughly 30%. Effectively, this means that despite the substantial increase in production volumes, absolute CED in the U.S. egg industry decreased almost 10%, while GHG emissions declined by 63%, acidifying emissions by 54%, and eutrophying emissions by 63%.

ANALYSIS ON DRIVERS OF OBSERVED DIFFERENCES IN IMPACTS BETWEEN 1960 AND 2010

Averaged across impact categories, impacts for egg production in 2010 were 60% lower than that of 1960 (Figure 9). By applying 2010 background system sub-models in the 1960 egg production model, 27-30% of the observed differences in acidification, eutrophication, and GWP were estimated to be attributable to changes in the efficiencies of background systems (such as fertilizer and feed input production, and transport modes). These outweighed the declining energy return on energy invested (EROI) ratio for primary energy carriers in these impact categories. For CED, however, applying 2010 energy carriers to the 1960 model resulted in 35% higher impacts in this category (Figure 9).

Using both 2010 background system models and feed composition in the 1960 egg production model, it was further estimated that changes in feed composition over time accounted for 30% of the observed decline in acidification potential for egg production in 1960 versus 2010, 35% for eutrophication potential, and 44% for GWP. Hence, it was estimated that changes in animal performance due to improved husbandry over the 50-year interval (e.g., improved feed conversion, lower mortality rates, etc.) were responsible for 43% of the observed decline in acidification potential, 35% for eutrophication potential, and 28% for GWP for egg production in 2010 compared to 1960. Despite declining EROI, CED in 2010 was only 30% that of 1960, due to a combination of changing feed composition and improved animal husbandry practices (Figure 9).

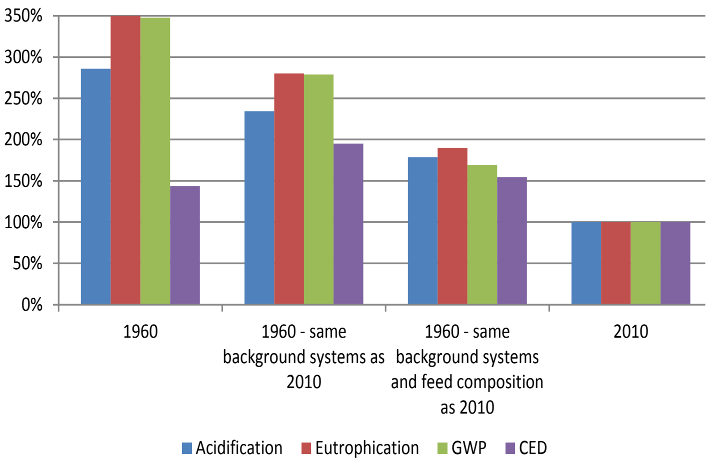


Figure 9. Scenario analyses to determine the relative contributions of assumed differences in background systems, feed composition, and animal husbandry performance to the estimated impacts for U.S. egg production in 1960 compared to 2010.

Despite a 30% increase in total U.S. egg production from 1960 to 2010, the absolute environmental footprint (cumulative energy demand, GHG emissions, acidifying emissions and eutrophying emissions) remains significantly lower for 2010.

COMPARISON WITH OTHER STUDIES

A limited number of time series analyses of the environmental impacts of animal husbandry are available. Capper et al. (2009) and Capper (2011) evaluated changes in the environmental performance of beef production in 1977 versus 2007, and dairy production in 1944 versus 2007. Considerable gains were documented in the resources (69.9% of animals, 81.4% of feedstuffs, 87.9% of the water, and 67.0% of the land required) to produce 1 billion kg of beef in 2007 compared to 1977, and commensurate decreases (16.3%) in associated GHG emissions. Similar gains in resource efficiency were estimated for dairy (21% of animals, 23% of feedstuffs, 35% of the water, and only 10% of the land required to produce 1 billion kg of milk in 2007 compared to 1944), while GHG emissions were 37% of 1944 levels. It should be noted that none of these studies (nor any of those discussed below) took into account changes in the resource efficiencies of background systems, hence are likely quite conservative. This study's estimates of the scale of resource efficiencies and emissions reductions for egg production between 1960 and 2010 are none the less comparable. In Canada, Verge et al. (2009) calculated direct GHG emissions from layer facilities along with crops used to produce layer feeds in 1981 compared to 2006. Indirect supply chain emissions were not considered, hence the study results are not comparable with those presented in the current analysis. It is interesting to note that these authors found the GHG intensity of egg production decreased from 1.9 kg of CO_2-e/dozen eggs in 1981 to 1.76 kg of CO_2-e/dozen eggs in 2006, or approximately 7% reduction over this 25-year interval. Cederberg et al. (2009) compared the GHG emissions from Swedish livestock production in 1990 and 2005 for pork, poultry meat, beef, milk and eggs. They found that the carbon footprint of pork production decreased from 4 to 3.4 kg CO_2-e/kg over this 15-year interval, whereas emissions for poultry meat decreased from 2.5 to 1.9 kg CO_2-e/kg, milk from 1.27 to 1 kg CO_2-e/kg, and emissions from beef increased from 18 to 19.8 kg CO_2-e/kg. Emissions from egg production remained unchanged at 1.4 kg CO_2-e/kg over this interval. This latter finding is in large part attributable to two factors: first, the phasing out of animal by-products in feeds that resulted from BSE issues; and second, the use of economic allocation. Despite efficiency gains in the sector, the allocation strategy resulted in a study outcome suggesting no net gains in environmental performance.

To date, no other estimates for the life cycle impacts of contemporary U.S. egg production are available. Pelletier et al. (2013) previously modeled egg production in Iowa using the same modeling approach as applied in this analysis. In the Iowa study the authors did not identify the sources (ruminant, porcine or poultry) of animal by-products and it was estimated the GHG emissions ranged from 2.0 kg of CO_2-e per kg of eggs (assuming 100% of the animal by-products were of poultry origin) to 5.0 kg of CO_2-e per kg of eggs (assuming 100% of the animal by-products were of ruminant origin).

Several studies are available, however, that report environmental performance for egg production supply chains in other countries. Although direct comparisons between studies are problematic due to frequent differences in modeling parameters (e.g, system boundaries for the studies, data sources, allocation rules, etc.), it is interesting to consider the range of reported impacts relative to those of the current study (Table 14).

Table 14. Reported life cycle impacts per kg of eggs produced in different countries.

STUDY	ACIDIFYING EMISSIONS (G SO_2-E)	EUTROPHYING EMISSIONS (G PO_4-E)	GHG EMMISSIONS (KG CO_2-E)	ENERGY USE (MJ)
U.S. AVERAGE (THIS STUDY)	70	20	2.1	12.3
UK[1]	53	77	2.9	16.8
NETHERLANDS[2]	32	25	3.9	-
SWEDEN[3]	-	-	1.4	-
CANADA[4]	-	-	2.5	-
AUSTRALIA[5]	-	-	1.4	-

(1) Leinonen et al. (2012)
(2) Mollenhorst et al. (2006)
(3) Cederberg et al. (2009)
(4) Verge et al. (2009)
(5) Wiedemann and McGahan (2011)

In broad strokes, the distribution of impacts along contemporary U.S. egg supply chains seems to be in general agreement with similar, previously reported LCA research of intensive, cage egg production systems elsewhere (Mollenhorst et al. 2006; Cederberg et al. 2009; Verge et al. 2009; Wiedemann and McGahan 2011; Leinonen et al. 2012). In a study examining the social, economic, and ecological dimensions of egg production by housing system in the Netherlands, Mollenhorst et al. (2006) used LCA as a basis for comparing performance in the environmental domain. Conventional cage production was found to perform better according to the environmental LCA variables considered, but the aviary system performed better according to the economic and animal welfare measures employed. In Australia, Wiedemann and McGahan (2011) used a life cycle approach to evaluate GHG emissions, energy and water use in egg production by housing system. Here, activity data were collected from four farms in eastern Australia. Cage systems were found to outperform free-range systems. Estimated impacts overall were low compared to results from most European studies. More recently, Leinonen et al. (2012) used top-down estimates of average UK production conditions in a standard, environmental LCA approach to characterize environmental performance for egg production in cage, barn, free-range, and organic systems. They reported highest impacts for organic production and lowest for cage production, largely due to differences in productivity (i.e., higher feed consumption and number of birds required per unit of egg production in the organic system). Feed production supply chains were the dominant contributor to GHG emissions and energy use (54-75% of the primary energy use and 64-72% of the GWP). Similar to our study, energy use in housing systems was the second most important factor for the overall energy intensity of egg production. Manure management contributed most to acidifying and eutrophying emissions.

The reason for lower estimated impacts in some studies compared to those of the present analysis, is that either animal by-products are not allowed for use in animal feeds in the countries of concern (e.g., the Swedish study by Cederberg et al. 2009), or that they were not included in the modeled feeds at all, whether or not they are actually used (e.g., the Australian study by Wiedemann and McGahan). In the latter study, the authors also point towards the low input nature of Australian grain production (compared to European norms) as an important factor influencing their reported outcomes. Considering the study of egg production in Sweden in 1995 compared to 2005 (Cederberg et al. 2009), the reduction in use of animal by-products, due to legislative changes, in-fact negatively impacted environmental performance in 2005 due to the use of economic allocation in this study. This is contrary to the results of the current analysis. This analysis shows an improved environmental performance over time by reducing the amount of animal by-products used in pullet and layer feeds. In light of the resource and emissions intensity of producing livestock (along with the livestock processing co-products used in animal feeds), it is suggested that the analytical approach used in current analysis better reflects the actual environmental costs of producing feed inputs for egg production, regardless of the economic value of such materials.

To put the GHG intensity of contemporary U.S. egg production in perspective, the following comparison is provided using the same methods. Pelletier et al. (2010a) estimated the GHG emissions per kg of porcine production in the midwestern U.S. at 3 kg CO_2-e per kg live weight produced. For conventional, feedlot beef production, estimated emissions were 14.5 kg CO_2-e per kg live weight produced (Pelletier et al. 2010b). Adapting the inventory data and methods of an earlier study of U.S. broiler production (Pelletier 2008) for methodological consistency with these analyses provides an estimate of 1.7 kg CO_2-e per kg live weight produced. In this analysis a GHG intensity of 2.1 kg CO_2-e per kg of eggs produced in the continental United States was estimated, compared to 7.2 kg CO_2-e per kg of eggs produced in 1960.

Making a similar comparison on the basis of protein, the GHG intensity of U.S. egg protein production (raw, from whole eggs) is 19.1 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 porcine protein, and 78.4 kg CO_2-e/kg of beef protein.

CONCLUSIONS AND RECOMMENDATIONS

Our analysis of the distribution and magnitude of life cycle impacts for egg production in the United States in 1960 compared to 2010 provides a clear indication of the scale of environmental performance gains, both per unit production and in aggregate, achieved by the industry over the past 50 years, as well as insights into the primary contributing factors. Several key insights emerge.

From a supply chain management perspective, the key leverage point for environmental performance improvements in egg production has been and will continue to be efforts to maximize feed use efficiencies, because feed production accounts for the largest share of impacts in egg production both in 1960 and at present. The feed conversion ratio for egg production improved from 3.44 in 1960 to 1.98 – an improvement of 42%. Nonetheless, achieving feed use efficiencies comparable to the best performing contemporary facilities (the range reported by survey respondents was 1.76-2.32) industry-wide would do much to further reduce aggregate impacts.

Changing feed composition has also played an important role in reducing impacts – in particular, both reduction in the total amount of animal-derived materials used as well as increased use of porcine and poultry materials in place of ruminant materials. The concept of least-environmental cost feed sourcing is therefore of particular relevance for additional targeted performance improvements for this industry. It is recommended that similar biophysical accounting methods to those applied in the current study be used to model potential alternative feed input supply chains to ensure methodological consistency and comparability with the present analysis.

Managing feed supply chains for environmental performance must also take into account nitrogen use efficiencies. N losses from poultry manure are the second largest contributor to acidifying and eutrophying emissions, as well as a non-trivial contributor to GHG emissions in both pullet and layer facilities. Moreover, upstream impacts of N fertilizer production and use are a primary determinant of feed input-related impacts. Feed formulation, breeding, and selecting manure management strategies for optimal N use efficiencies are therefore powerful tools in supply chain environmental management. This analysis modeled N losses using standard IPCC protocols. Given the margin of error associated with manure N sampling, it is recommend using this IPCC-based modeling approach. This will also maximize inter- and intra-company and product comparability. However, continued efforts to improve and standardize company-level manure-N sampling accuracy is suggested, in order to allow for differentiation between facilities and production strategies looking forward.

Overall, our analysis provides compelling evidence that considerable strides in resource use efficiency and animal husbandry performance in the U.S. egg sector over the past 50 years have greatly reduced both the relative and absolute environmental impacts of U.S. egg production. Also apparent, however, is that there remains substantial scope for continued improvement. Moreover, in light of continued declines in EROI for energy carriers consumed in egg supply chains, continuous improvement will likely be necessary simply to maintain the current status quo environmental footprint of the U.S. egg sector. The benchmarks reported here, as well as the reported ranges for resource use and production efficiencies in what are, ostensibly, otherwise similar production facilities, provide an excellent reference point for industry-led initiatives for further improving the environmental performance of U.S. egg production.

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LIST OF TABLES

LIST OF FIGURES

KEYWORDS: Eggs, life cycle assessment (LCA), pullets, production performance, environmental footprint, energy return on energy invested (EROI)

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