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A retrospective analysis of the United States poultry industry: 1965 compared with 2010

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ABSTRACT

The U.S. poultry industry requires a comprehensive understanding of the driving forces behind the changes in the environmental performance of poultry meat production in order to implement an effective sustainability strategy. This life cycle assessment (LCA) evaluates those changes over the past 45 years so that the industry can prioritize improvements to aspects of production that will have the greatest effect on the environmental impacts associated with poultry production. The LCA included material and energy flows associated with crop production and live poultry operations, beginning with one day old baby chicks in the grandparent generation, continuing through the parent generation, and ending with live market-weight broilers and culled hens at the farm gate. The results indicated that improvements in background systems and bird performance were the primary drivers behind a reduction in environmental impacts and decreased resource requirements in U.S. poultry meat production in 2010, as compared to 1965. Climate change, acidification, and eutrophication impacts associated with poultry production decreased by 36%, 29%, and 25% per 1000 kg poultry meat produced, respectively, from 1965 to 2010. Furthermore, resource-related impacts decreased in the categories of fossil energy use (39%), water depletion (58%), and agricultural land occupation (72%) per 1000 kg of poultry meat produced. This study provides the first retrospective analysis of poultry meat production in the United States, and the only U.S. poultry LCA that incorporates spent hen meat destined for human consumption and successive breeding generations into an analysis of broiler production. These methodological considerations provide greater insight into the impacts associated with U.S. poultry supply chains than was previously available, which will allow the U.S. poultry industry to make more informed decisions regarding an effective sustainability strategy and will increase publicly-available LCI data with contributions to the National Agricultural Library's LCA Commons.

1. Introduction

As the global population continues to increase, the agriculture sector is faced with arguably the most significant challenge to human prosperity: How to produce more food utilizing a finite set of resources while reducing impacts to the environment. In order to meet this challenge, innovation and intensification will be required if current consumption rates are to be maintained. Failure to improve the efficiency of our food production systems will necessitate allocating far more of our natural resources to agriculture (Schneider et al., 2011). Continuous improvement in agriculture is especially relevant for the livestock sector because animal-based products tend to have higher environmental impacts than their plant-based counterparts (Heller et al., 2013). These impacts are exacerbated as the global demand for meat continues to rise (MacLeod et al., 2013). As the largest producer and second-largest exporter of poultry meat in the world, the U.S. poultry industry has a critical role to play in reducing the sector's environmental footprint.

Life Cycle Assessment (LCA) is a quantitative environmental method used to compile and assess environmental impacts of products, processes, and services over their entire life cycle. Extensive food databases such as the World Food LCA Database, Agri-footprint, and Agribalyse have been developed (Nemecek et al., 2014; Blonk Agri Footprint BV, 2015; Koch and Salou, 2015), demonstrating the food sector's adoption of LCA as the standard methodology for measuring and reducing environmental impact. Retrospective analysis is one method used to better understand these environmental impacts through time. These analyses provide valuable insight into the changes in production processes between two points in time and highlight those aspects that have improved considerably as well as those that require more attention. Such analyses have been conducted for livestock industries across the world (Dyer et al., 2008; Vergé et al., 2008a; Vergé et al., 2008b; Vergé et al.,

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2009; Cederberg et al., 2009; Wiedemann et al., 2015) and for all major livestock industries in the United States, except poultry (Capper et al., 2009; Capper, 2011; Boyd et al., 2012; Pelletier et al., 2014).

In this study, we use LCA methods to conduct a retrospective analysis of U.S. poultry production. The primary objectives of this study are (1) to quantify the different material and energy flows required for broiler production in 1965 and 2010 and (2) to characterize their effects on the environment using LCA. The fossil energy use, water consumption, and land occupation requirements along with the climate change, acidification, and eutrophication potentials are quantified per 1000 kg of live weight poultry meat produced for human consumption. The elements of production that have the greatest impact on change are assessed in order to share this information with the U.S. poultry industry so that the producers, integrators, and distributors can use this knowledge to improve poultry production in the future. Additionally, the lifecycle inventory (LCI) data will be submitted to the National Agricultural Library's LCA Commons to support future U.S. agriculture LCAs.

2. Methods

The LCA in this study utilizes deterministic models based on industry and literature data to approximate the national average of poultry production in the United States for the years 1965 and 2010. The functional unit is one thousand kilograms (1000 kg) of live weight (LW) poultry meat and spent hens destined for human consumption at the farm gate, ready for transport to the processor. The system boundaries include all material and energy flows associated with crop production and live poultry operations, including the handling and disposal of mortalities and manure. Previous studies estimate between seven to 8% of the environmental burdens associated with the production of broiler meat comes from the breeding process (Leinonen et al., 2012; Wiedemann et al., 2012). Therefore, inventory flows began with one day old baby chicks in the grandparent generation, continued through the parent generation, and ended with live market-weight broilers and culled hens ready for transport to processing at the farm gate (Fig. 1). Where applicable, the recommendations of the Livestock Environmental Assessment and Performance (LEAP) Partnership were followed, which provided guidelines for assessing the greenhouse gas emissions (GHG) and fossil energy use from poultry (LEAP, 2015a) and animal feed supply chains (LEAP, 2015b). These guidelines were developed with poultry producers in mind, with the intention of providing a transparent methodology for identifying opportunities to increase efficiency and benchmark performance. The preliminary results from our scoping analysis suggested that the grandparent generation had a minimal contribution to the functional unit. Therefore, the great-grandparent generation was not included in our analysis, as suggested by the LEAP guidelines. Impacts were not included that were associated with the manufacture and maintenance of capital goods, chemotherapeutics, cleaning agents, or water use outside of drinking and cooling water, e.g., water used for cleaning.

2.1. Life cycle inventory

2.1.1. Crops and feed rations

National datasets from the U.S. Department of Agriculture (USDA) were used in both reference years to estimate life cycle inventory (LCI) data for crop yields, fertilizers, and pesticides for the corn, wheat, soy, and alfalfa products used in poultry rations (USDA ERS, 2013; Fernandez-Cornejo et al., 2014; USDA NASS, 2015). Crop yields were determined using multi-year national averages, covering the five years prior to the reference year. Fertilizer application rates were representative of the year 1964 and 2010 because data for 2006–2009 and prior to 1964 were unavailable. Nitrous oxide emissions resulting from mineral fertilizer application were calculated according to IPCC guidelines using default emission factors (IPCC, 2006). Crop residue emissions of N_2O and NH_3 were calculated using the same IPCC methods. Furthermore, we assumed 10% of applied nitrogen volatilized as ammonia, while another 30% leached to freshwater as nitrate (Blonk Agri Footprint BV, 2015). At the time of this research, there was no single, comprehensive data source that quantified the irrigation water use in U.S. crop production. Therefore, a combination of sources was employed to estimate the irrigation water use in 2010 (USDA FRIS, 2009; USDA NASS, 2009) and in 1965 (Murray, 1968; USDA, 1964). Inventory data of the three primary crops fed to poultry are presented in Table 1.

Ration compositions were adapted from the Commercial Poultry Nutrition textbook (Leeson and Summers, 2009) for 2010 and from Poultry Science and Practice (Winter and Funk, 1960) for 1965. The contributions of the major feed ingredients to rations consumed in each stage of poultry production are presented in Table 2.

2.1.2. Live poultry production

Deterministic, spreadsheet-based models were built to estimate the growth, feed consumption, and mortality rates for live poultry production. Three bird models were created to represent the different stages of poultry farming, including broiler production, pullet production, and egg production. The models were then adapted to represent each generation and reference year. The egg production model included resource requirements and emissions associated with hens, roosters, and the disposal excess male chickens throughout the broiler breeder (parent) generation. Data from the performance objectives tables for the Arbor Acres genetic line by Aviagen were used to construct growth curves in the 2010 poultry models (Arbor Acres, 2011a, 2011b, 2014). For the 1965 poultry models, all growth curves were developed using experimental data published in the textbook, *Poultry Science and Practice* (Winter and Funk, 1960). Next, historical data published by the National Chicken Council (NCC) were implemented to set the marketing ages in the models and then compare the outputs for feed conversion ratio (FCR), market weight, and mortality with the values published by the NCC for verification (National Chicken Council, 2015). Furthermore, drinking water was estimated to be two kg of water for every kilogram of feed consumed for both reference years (Patrick and Ferrise, 1962; Leeson and Summers, 2009), which accounted for spillage and evaporation.

In the 1965 production models, the grandparent and parent generation had identical production practices. Both generations raised pullets to 21 weeks of age on the same farm as the hens (Table 3), thereby assuming no transport between pullet rearing and the laying houses. The grandparents produced more eggs per hen than the parents (191 eggs vs. 176 eggs), but experienced a higher mortality rate (20.5% vs. 15.1%) and consumed more feed per spent hen (59 kg vs. 58 kg). All hens had a laying period of 41 weeks, resided in naturally ventilated houses, and used community nesting boxes (Table 4).

Comparatively, in the 2010 models, poultry breeding was much more specialized with the grandparent production practices barely resembling those of the parent generation. The grandparents, referred to as the primary breeders, were bred in small flocks that consisted of two different genetic lines. One genetic line of mates was used to produce the males (male line) in the parent generation, the other for the females (female line). Male line hens produced 128 eggs during their laying period and female lines produced 171 eggs. Both lines experienced 8% mortality (Table 4). Nearly 30% of the grandparent generation (mostly the males) were culled prior to mating to ensure the most desirable characteristics were inherited by the parent generation. This practice of selective breeding inflated the ratio of feed consumed to eggs produced because some of the birds that were fed, never become part of the mating process. Primary breeding facilities were climate-controlled environments, relying on electricity for heating and cooling with diesel generators in case of power outages. Only pullet rearing used supplemental heat provided by propane gas heaters. Conversely, the parent generation relied on fans and natural ventilation for climate control.

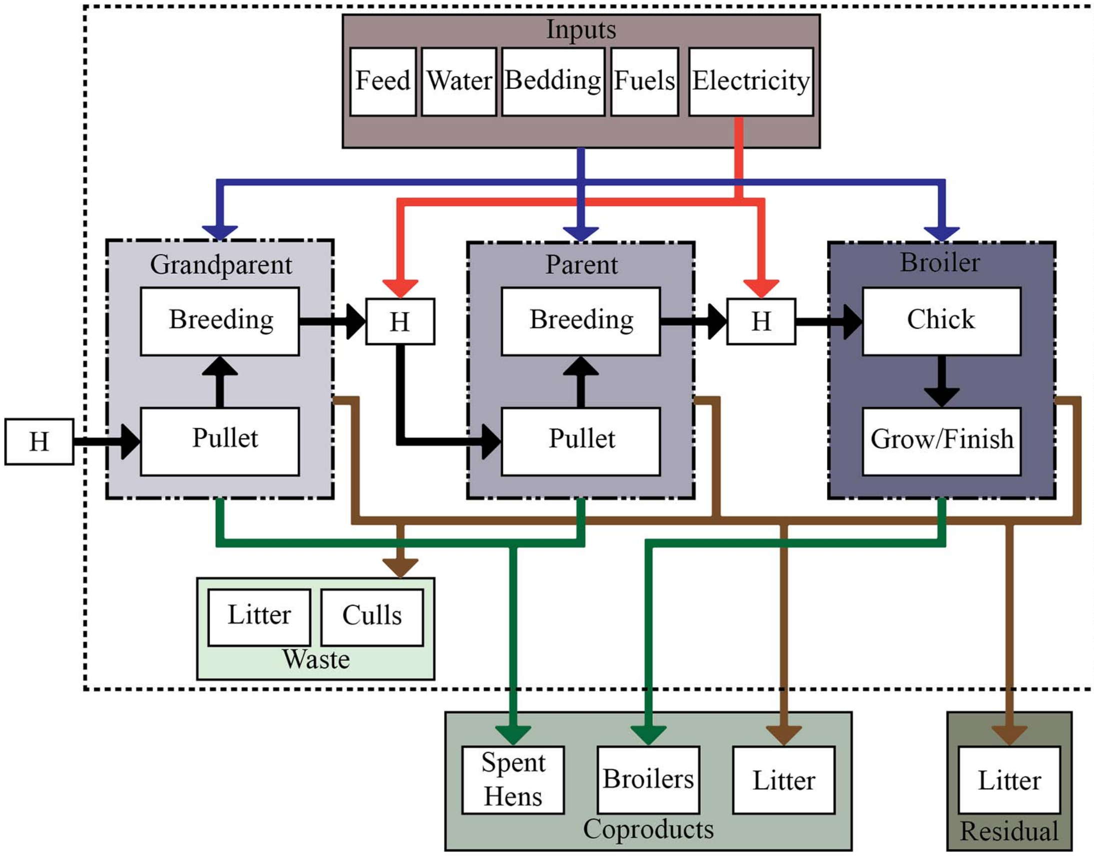

Fig. 1. Inputs, outputs, and system boundaries for the live poultry production model representing 1965 and 2010. Background system inputs are represented by the blue and red arrows, with the red arrows indicating electricity as the sole input. Black arrows outside of the purple boxes represent transport between farms and hatcheries, and those within the boxes represent movement between barns, or in the case of broilers, a management alteration required to transition from brooding to finishing. Green arrows indicate contributions to the functional unit and brown arrows represent waste products. The boxes marked "H" represent hatcheries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
The LCI data for the primary crops used in poultry rations of 1965 compared to 2010, expressed as 1000 kg crop produced. Alfalfa was part of the feed ration in 1965, but was not a component of the 2010 ration.

	Corn			Soybeans			Wheat		
	1965	2010	Change	1965	2010	Change	1965	2010	Change
Inputs									
Land (m^2)	2543	1039	− 59%	6183	3510	− 43%	5888	3535	− 40%
Irrigation water (m^3)	40	51	25%	44	74	69%	211	107	− 49%
Herbicide (kg)	0.12	0.27	123%	0.13	0.55	312%	0.07	0.13	94%
Insecticide (kg)	0.07	0.01	− 92%	0.03	0.02	− 20%	0.01	0.01	− 40%
N, fertilizer (kg)	14.1	15.8	13%	0.7	1.1	67%	8.4	22.2	164%
P, fertilizer (kg)	8.4	5.5	− 35%	2.5	4.2	67%	6.4	7.6	19%
K, fertilizer (kg)	8.4	5.7	− 32%	25.7	31.5	23%	3.6	1.5	− 58%
Diesel (L)	16.3	5.2	− 68%	39.4	17.1	− 57%	38.3	17.4	− 55%
Fuel oil (L)	7.1	6.9	− 3%	10.4	10	− 4%	8.4	7.5	− 10%
Electricity (kWh)	66.3	32.5	− 51%	67.7	47.8	− 29%	117.6	69.2	− 41%
Emissions									
N2O, residues (kg)	0.14	0.14	− 1%	0.31	0.24	− 22%	0.26	0.24	− 8%
NO3, residues (kg)	10.53	9.61	− 9%	21.29	16.71	− 21%	17.9	16.57	− 7%
N2O, fertilizers (kg)	0.29	0.33	14%	0.01	0.02	136%	0.17	0.46	172%
NH3, fertilizers (kg)	1.71	1.92	12%	0.08	0.14	72%	1.02	2.69	164%
NO3, fertilizers (kg)	18.71	19.24	3%	0.9	1.38	53%	11.15	26.95	142%
PO4, fertilizers (kg)	0.87	0.57	− 35%	0.26	0.43	66%	0.67	0.79	18%

Also, pullets were reared on a separate facility and were transported 3 km to the laying houses.

The 1965 broiler model assumes 3.5 kg of feed consumed per bird and a 6% mortality for birds marketed at 1.59 kg. The broiler production cycle in this model lasted 63 days and required 14 days between cycles for cleaning. Comparatively, the 2010 production model shows 5.0 kg of feed consumed per bird and 4% mortality for broilers marketed at 2.59 kg. It also shows that one broiler production cycle lasted 47 days and required 17 days between cycles to clean and prepare for the next flock. In 1965, a broiler consumed 2.4 kg of feed for every kg of weight gain (FCR = 2.4); whereas in 2010, a broiler consumed 1.94 kg of feed for one kg of gain (Table 5).

Table 2
Poultry feed rations for each bird type in 1965 and 2010. The feed ingredient fractions for hens and pullets of 2010 are averages of the parent and grandparent generation. In 1965, the breeding generations consume the same ration.

Feed ingredient	Broilers		Pullets		Hens	
	1965	2010	1965	2010	1965	2010
Corn	31.7%	64.2%	50.2%	53.8%	63.9%	59.3%
Wheat	29.7%	3.1%	28.8%	25.8%	10.0%	0.5%
Soy	28.9%	24.0%	10.4%	16.7%	12.0%	21.0%
Alfalfa	2.0%	0.0%	3.2%	0.0%	2.5%	0.0%
Meat/fish meal	0.0%	4.9%	3.7%	0.0%	5.0%	6.4%
Limestone	2.0%	1.1%	1.5%	2.0%	3.8%	10.1%
Fat/tallow	4.0%	1.7%	0.2%	0.0%	1.0%	2.1%
Other[a]	5.7%	1.0%	2.3%	1.6%	2.8%	0.5%

[a] Includes salt, limestone, vitamins, minerals, and synthetic amino acids (in 2010 rations only).

Table 3
LCI data for the 1965 and 2010 pullet models. Inputs and outputs are presented based on 1000 pullets reared.

	G1		G2	
	1965	2010	1965	2010
Inputs				
Baby chicks	1104	1087	1104	1045
Feed	13,586	11,329	13,586	8608
Water (kg)	27,172	22,658	27,172	17,216
Diesel (gal)	14	19	14	30
Electricity (kWh)	726	998	726	1553
LPG (gal)	107	147	107	230
Bedding (kg)	223	307	223	478
Outputs				
Litter (bedding + excreta) (kg)	3846	3328	3846	5714
Mortalities (kg)	155	434	155	127
Reared pullets	1000	1000	1000	1000
Production parameters				
Pullet mortality	10.4%	8.0%	10.4%	4.5%
Pullet cycle	146	146	146	146
Reared weight (kg)	2.76	2.3	2.76	2.30
Feed conversion ratio	4.75	4.93	4.75	3.74

Hatcheries were assumed to have the same energy requirements in both reference years, and only electricity use was considered. The electricity required to produce one hatched egg was estimated to be 0.0812 kWh (Nielsen et al., 2011). While this was likely not the same for 1965, the literature review and scoping analysis suggested that hatcheries have a relatively minor contribution to the impacts associated with modern poultry production and quality inventory data necessary to assess the potential impacts of hatcheries in the 1960s was unavailable.

2.1.3. Resource use on farm

LCI data for electricity, heating fuel, and diesel consumption for the broiler models were derived from energy audits conducted by university extension offices in Arkansas, Georgia, and Kentucky. The annual average use for each state was weighted by the 2010 annual broiler production to get national averages for three energy sources (Table 6). These national averages were normalized to a kilogram of LW broiler. The values of the output-normalized utility consumption were applied to both reference years to estimate consumption for the life cycle inventory (Table 7). Only Dunkley et al. (2015) included data for pullet and breeder operations in Georgia so the utility consumption of breeding barns was based solely on that data. Although poultry production practices—types of lightbulbs or ventilation systems—varied significantly between 1965 and 2010, variations in energy use were more likely attributable to the operator than to any one specific operational attribute (personal communication with Dr. Yi Liang). Cooling water use was also determined using output-normalized values based on extension data (Liang et al., 2014). No water use for cooling in 1965 was assumed because tunnel-ventilated water cooling systems were essentially nonexistent, whereas cooling water use in 2010 was considered standard.

Table 4
LCI data for the 1965 and 2010 hen models. Inputs and outputs are presented based on 10,000 hatched eggs.

	G1		G2	
	1965	2010	1965	2010
Inputs				
Pullets	129	88	134	72
Roosters	11	9	12	7
Feed (kg)	6863	4322	7146	3026
Water (kg)	13,726	8644	14,293	6051
Diesel (l)	43	7	41	7.6
Electricity (kWh)	395	242	373	217
LPG (l)	0.3	0.0	0.2	0.0
Bedding (kg)	8.5	6.4	8.8	4.7
Outputs				
Spent hens	103	56	113	66
Live weight (kg)	360	226	395	254
Eggs	17,544	13,521	17,544	12,151
Litter (bedding + excreta) (kg)	1839	952	1915	813
Mortalities (kg)	83	33.9	66	18
Hatched eggs	10,000	10,000	10,000	10,000
Production parameters				
Hen mortality	20.5%	13.0%	15.8%	8.0%
Hen eggs	190	163	167	186
Spent weight (kg)	3.50	4.00	3.50	3.86
Feed per hen (kg)	59.1	76.7	58.0	44.0
Feed per dozen eggs (kg)	3.73	3.84	4.16	2.84
Laying period (wks)	41	44	41	44
Hatch percentage	57%	79%	57%	82%

Table 5
LCI data for the 1965 and 2010 broiler models. Inputs and outputs are presented based on 1000 market weight broilers.

	1965	2010
Inputs		
Baby chicks	1060	1040
Feed (kg)	3798	5021
Water (l)	7596	10,043
Diesel (l)	11	5
Electricity (kWh)	138	225
LPG (l)	73	31
Bedding (kg)	212	208
Outputs		
Litter (bedding + excreta) (kg)	1225	1547
Mortalities (kg)	44	55
Broilers	1000	1000
Live weight (kg)	1590	2591
Production parameters		
Broiler mortality	6%	4%
Production cycle length (days)	63	47
Market weight (kg)	1.59	2.59
Feed conversion ratio	2.39	1.94

2.1.4. Background systems

The U.S. Ecoinvent v2.2 database (Frischknecht et al., 2007) was used to estimate the upstream impacts associated with background systems, i.e. energy, transportation, and raw material production. Some of the unit processes were adapted to represent less efficient systems typical of 1965, and occasionally were adapted for more efficient systems of 2010. According to data from the Nebraska Tractor Test

Table 6
Utility use per 1000 kg of LW broiler marketed in three states and the weighting factor used to compute national averages.

State of origin	Utility			2010 Production[a]	Weighting factor
	Diesel (gal)	Electricity (kWh)	Propane (gal)		
Georgia[b]	0.56	79.9	11.7	6,874,400	48%
Arkansas[c]	–	96.0	12.2	5,780,000	40%
Kentucky[d]	–	84.9	13.0	1,657,800	12%

[a] USDA NASS, 2016.
[b] Dunkley et al., 2015.
[c] Unpublished data.
[d] Kentucky Poultry Federation, 2014.

Table 7
Life cycle inventory data for utility consumption for each of the bird models.

Type of barn	Utility			Unit
	Diesel (gal)	Electricity (kWh)	Propane (gal)	
Broiler[a]	0.556	88.0	12.1	per 1000 kg LW
Breeder[b]	0.165	17.9	0.003	per 1000 eggs
Pullet[b]	4.00	650	96.1	per 1000 pullets

[a] Production-weighted averages.
[b] Only includes data from Dunkley et al., 2015 (Georgia).

Laboratory, specific fuel consumption for tractors sold in the U.S. in the early 1960s was 31% higher for drawbar power and 25% higher for power take-off than for those sold in the early 2010s (Hoy et al., 2014). Based on this assessment, fuel consumption was estimated to be 1.31 times greater for field operations (per acre harvested) in 1965 crop production. Power take-off was used a proxy for general use motors, and as such, energy use associated with irrigation systems and diesel generators in 1965 was increased by 1.25 to represent the less efficient equipment of that time. The Transportation Energy Data Book (US-DOE, 2016) published statistical data for the energy intensities of freight modes going back to 1970. Linear regressions were developed using this data to extrapolate back to 1965 and create scaling factors for transportation via road (1.18), rail (3.09), and water (1.69). These scaling factors were applied to transport distances in 1965. The same approach was taken regarding nitrogen fertilizer unit processes in the U.S. Ecoinvent database, which were representative of production processes in 1997. A report by the International Fertilizer Industry Association provided the energy efficiency of ammonia production plants from 1955 to 2008. The data in this report was used to derive scaling factors of 1.31 for 1965 and 0.88 for 2010 (IFA, 2009). These scaling factors were applied to the energy requirements within the U.S. Ecoinvent unit processes for nitrogen fertilizer production. Production efficiencies of all other material inputs were assumed to be equivalent in 1965 and 2010; however, the composition of power generation sources for the electricity grid mix was altered to represent 1965 and 2010. Line losses and other conversion efficiencies were assumed to be the same. The annual contribution of electricity generation in the U.S. by power source for both reference years is presented in Table 8.

Table 8
Power generation sources for the electricity grid in 1965 and 2010 according to the U.S. Energy Information Administration (US EIA, 2016).

Year	Power source						
	Coal	Petroleum	Gas	Nuclear	Hydro[a]	Wind	Other[b]
1965	53.9%	6.1%	20.9%	0.3%	18.6%	0.0%	0.0%
2010	44.9%	0.9%	24.3%	19.6%	6.2%	2.3%	1.8%

[a] Net generation from conventional hydro and pumped storage hydro.
[b] Includes electricity generated from wood, waste, geothermal, and solar sources.

2.1.5. Manure management

Excreta from broiler and pullet operations in both reference years was deposited on floors lined with wood shavings and was collected yearly and then transported off the farm. For egg production, only one third of the barn was lined with bedding, which was removed at the end of each laying cycle. The remaining floor space was covered by the nesting area, which had permeable flooring, allowing excreta to collect underneath. Excreta and bedding (collectively called litter) from all poultry operations were transported off the farm and applied as fertilizer. Bedding requirements and manure production were derived from estimates described by Leeson and Summers (2009) and used to construct linear relationships with poultry production parameters. For example, the amount of bedding material required was directly correlated to the number of broilers or pullets in a barn (0.2 kg wood shavings per bird), and the amount of feed consumed per bird determined the mass of manure produced (0.27 kg DM excreted per feed consumed). Bedding requirements for hens were calculated using the same relationship defined for pullets, only reduced by 67% to reflect the barn area covered by nest. Once these feed and bedding relationships were established, they were then applied to the poultry models of both reference years. Additionally, emissions of N_2O, CH_4, and NH_3 from excreta in the poultry house were calculated using IPCC Tier 1 default emission factors and nitrogen excretion rates. Notably, bedding materials contain large quantities of nitrogen, but the mineralization of these compounds prior to field application is negligible (IPCC, 2006).

2.2. Treatment of coproducts and waste

Impacts associated with the transport, application, and subsequent emissions of poultry litter were modeled in agreement with the LEAP guidelines (LEAP, 2015a), which dictate the attribution of these burdens according the economics of litter removal. We modeled litter removal and disposal between three classifications according to national averages for 2010 (USDA, 2011a,b). We applied those classifications to poultry litter in both reference years, as data regarding poultry litter transactions were unavailable for 1965 (Table 9).

Table 9
The nature of transactions regarding poultry litter disposal in the U.S. and their consequences on output classification according to LEAP guidelines. The fraction of litter in each classification is the percentage of total litter produced, treated as a coproduct, waste, or residual. The term "bartered" refers to litter that has been given away in exchange for a service, which is often the act of cleaning the litter out of the barn and hauling it away.

Disposal transaction	Fraction of litter from		
	Broilers[a]	Breeders[b]	Classification
Sold	50.0%	36.3%	Coproduct
Hauled off for fee	3.20%	4.2%	Waste
Bartered	36.1%	39.0%	Residual
Given away	10.7%	20.5%	Residual

[a] USDA, 2011a.
[b] USDA, 2011b.

Table 10
Allocation of poultry model outputs using the biophysical approach outlined by LEAP (2015a).

Hen model outputs	Allocation fraction	
	Hens	Broilers
Eggs	47%	NA
Live weight	42%	90%
Litter	11%	10%

Allocating resources and environmental burdens is necessary when a product system has multiple outputs and cannot be divided into subprocesses or expanded to include the functions of all co-products (ISO, 2006). For the most part, the inclusion of spent hens in the functional unit avoids the problem of allocation. An issue arises when the removal of poultry litter contributes revenue to the operator and must then be classified as a coproduct. In such cases, we allocated impacts to poultry litter using the biophysical approach outlined by the LEAP guidelines (LEAP, 2015a). The allocation fractions for hens and broilers are presented in Table 10. A full description of the biophysical allocation methods is included in the electronic supplementary material (ESM).

When coproducts were used as a ration component, impacts were allocated on the basis of their mass-adjusted caloric energy content. This method of allocation was used for the purposes of comparability between 2010 and 1965 feedstuffs and because the energy content of the feed consumed formed the basis of the biophysical allocation procedure applied to poultry co-products. The use of caloric energy as a basis for allocation in animal feeds allowed for the material and energy flows to follow the flow of caloric energy throughout the feed and poultry supply chains. The allocation of burdens to coproducts on the basis of their caloric value represents an underlying physical relationship, which is the recommended approach in situations where system expansion cannot be applied (ISO, 2006).

2.3. Characterization models

The impacts associated with poultry production were evaluated according to three resource-related categories (fossil energy use, water consumption, and land occupation), in addition to three emission-related impact categories (climate change, acidification, and eutrophication). Impact calculations were made using the LCA modeling software, SimaPro 8.1. Characterization factors for the environmental impact categories were provided by TRACI 2.1, an impact assessment tool developed by the EPA specifically for application in the United States (Bare, 2012). Emission-related impacts were expressed as (1) carbon dioxide equivalents (CO2-eq) for global warming potential (GWP), (2) sulfur dioxide equivalents (SO2-eq) for acidification, and (3) nitrogen equivalents (N-eq) for eutrophication.

2.4. Interpretation

Additional analyses were conducted in the interpretation stage to quantify uncertainty, determine the sensitivity of the results to our methodological choices, and to quantify impacts from those aspects of production which had the greatest contribution to change between the reference years. Uncertainty analysis provides quantitative evidence of statistical significance (Leinonen et al., 2013), which we conducted via 1000 Monte Carlo simulations for each reference year at a confidence interval of 95%. Lognormal distribution values were assigned to all foreground processes using the pedigree matrix approach. Inventory flows were assigned data quality scores of “2” for 2010 and “3” for 1965 in each of the five data quality indicator categories. We used literature values for the basic uncertainty factors (Pedersen et al., 1996). Results for each impact category were independently tested for significant differences using a student *t*-test that assumed unequal variances. Sensitivity analyses were conducted with regard to litter classification. Alternate scenarios were developed in which litter was treated strictly as a coproduct, a residual, or as a waste. Results from the alternate scenarios where then compared to the baseline.

In addition to the uncertainty and sensitivity analyses, a contribution analysis was performed. The purpose of this analysis was to isolate specific aspects of poultry production and the upstream supply chain to determine their contribution to the change in impact from 1965 to 2010. Three aspects were identified for the contribution analysis: bird performance, feed ration composition, and background systems. Bird performance was determined by running the 1965 model with the background systems and feed rations of the 2010 model in order to identify the influence of poultry-specific advances, i.e. improvements in nutrition, breeding, housing, etc. The influence from differing feed ration compositions was determined by running the 1965 model with the feed ration composition from 2010. All other aspects of the 1965 were kept the same, including the background systems. Feed rations were chosen in order to quantify the influence from the 2010 ration mix, isolated from the influence of any other changes, i.e. improved crop production or poultry husbandry. The third aspect of the contribution analysis was performed in order to account for the differences in the background systems, which included the electricity grid mix and crop sub models, and involved substituting the background systems in the 1965 model with those from the 2010 model. This aspect of the contribution analysis was chosen as a representative example of the influence from aspects outside of the control of the poultry operator.

3. Results and discussion

3.1. Life cycle impact assessment

We found that the U.S. production of poultry meat in 2010 had lower environmental impacts and required fewer resources when compared to production in 1965 for all categories. The improvements over 1965 were found to be significant in all impact categories at a confidence interval of 95%. The production of 1000 kg of live weight

Table 11
Life cycle impact assessment results from 1000 kg of LW poultry produced for human consumption in 1965 and 2010, with impacts broken down by contribution from broilers and spent hens.

Impact category	Unit	1000 kg LW poultry			Broiler contribution		Hen contribution	
		1965	2010	Change	1965	2010	1965	2010
GWP	kg CO_2 eq.	1991.5	1280.0	− 36%	1847.0	1226.4	144.5	53.6
Fossil energy	MJ	20,502	12,551	− 39%	19,156	12,046	1345	505
Water	m^3	271.35	113.21	− 58%	254.48	108.54	16.87	4.68
Ag. land	m^2a	11,241	3152	− 72%	10,600	3022	641	130
Acidification	kg SO_2 eq.	64.65	45.75	− 29%	60.02	43.98	4.63	1.78
Eutrophication	kg N eq.	28.08	21.00	− 25%	25.67	20.06	2.41	0.93

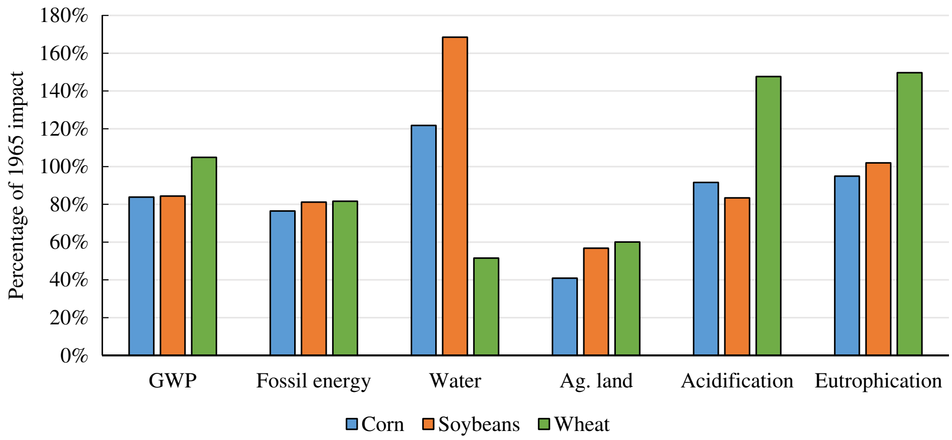

Fig. 2. LCIA results for the primary poultry feed ration components in 2010 as compared to 1965.

poultry in 2010 required 39–78% fewer resources and had 26–50% less environmental impact potential than the equivalent amount produced 45 years before (Table 11). Crop production, e.g., higher yields, and bird performance, e.g., lower FCR, were the primary drivers of improvement between the two reference years. Feed rations, particularly those of broilers, made up the largest portion of the environmental impact and resource depletion categories, with the exception of acidification.

Corn, wheat, and soybeans, which make up the bulk of poultry rations in both reference years, mostly showed improvement from 1965 (Fig. 2). While corn and soybeans require more water, both crops had lower impacts in nearly every other category in 2010. The only exception is soybeans, which have a slightly higher association with eutrophying impacts (+1.9%) due to higher application rates of mineral fertilizers containing phosphorous and nitrogen. Wheat performed the worst of the three staples, with three out of the six categories showing increased impact potential. In 2010, wheat received more than double the amount of nitrogen fertilizer than in 1965, which increased the impacts associated with climate change (5%), acidification (48%), and eutrophication (50%). However, all three of the resource-related categories exhibited improvements.

The LCIA results suggest very little impact contribution to the functional unit from the grandparent generation in either reference year. The total influence from all primary breeding operations combined was approximately 0.1% in each impact category (Fig. 3). This result was not surprising, considering each grandparent hen is responsible for the eventual birth of around 10,000 broilers. The results suggest a greater environmental impact from the grandparent progeny of 2010 than those of 1965, despite the minor contribution to the overall impact associated with poultry production.

The impact contribution from the parent generation on poultry meat production ranged from 12% to 22% in 1965, and from 8% to 12% in 2010 (Fig. 3). Hens from 2010 experienced a lower mortality rate and laid more fertile eggs than their 1965 counterparts, which spread out their contribution across more baby chicks and thus reduced the overall environmental burden from that generation. In addition to increased production, the hens of 2010 had a slightly heavier market weight, which further dilutes their impact contribution because one spent hen contributed more meat to the functional unit than one in 1965.

The remaining portion and the majority of environmental burdens were associated with broiler production. This is to be expected as broiler meat is also a significant majority of the meat produced from the poultry supply chains of both reference years. The results are mixed for the environmental impacts attributed to broilers between the two time periods. Global warming potential, acidification, and eutrophication impacts were greater in 2010 on a per bird basis, but a heavier market

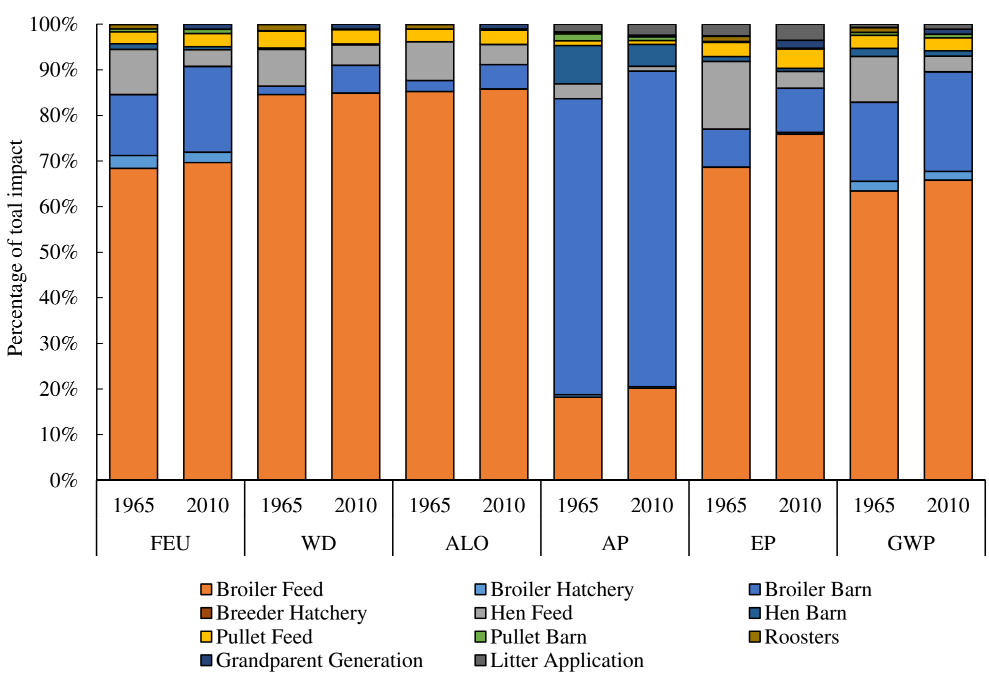

Fig. 3. Relative contributions from poultry production barns, feed rations, and litter application to emission-related impact categories (eutrophication (EP), acidification (AP), and global warming potential (GWP)) and resource-related impact categories (agricultural land occupation (ALO), water depletion (WD), and fossil energy use (FEU)) towards the production of 1000 kg LW poultry. This is representative of U.S. national average values for 2010 and 1965. Production barns and feed rations are combined into one group for the grandparent generation.

Table 12
Total impact for the U.S. poultry industry in 1965 and 2010.

Item	1965	2010	Increase from 1965
Total LW poultry produced ($\times 10^6$ kg)	4228	22,705	437%
Global warming potential ($\times 10^6$ kg CO_2e)	8754	30,209	245%
Non-renewable fossil energy ($\times 10^6$ MJ)	90,077	295,502	228%
Water depletion ($\times 10^6$ m^3)	1151	2585	125%
Agricultural land occupation ($\times 10^6$ m2a)	47,531	71,580	51%
Acidification ($\times 10^6$ kg SO_2-eq.)	276	1048	279%
Eutrophication ($\times 10^6$ kg N-eq.)	136	540	297%

weight moved all categories in a positive direction when impacts were considered on the basis of live weight. Fossil fuel use also increased (per broiler) in 2010, but the difference was minimal (1.4%).

3.2. Total industry impact

Poultry production in the United States grew more than five-fold from 1965 to 2010, with the national output surpassing 50 million lbs. of LW poultry (USDA NASS, 2016). While the impacts associated with producing 1000 kg of LW poultry meat declined between the reference years, the growth experienced by the industry changed at a much faster rate. Table 12 presents the impact assessment results applied to the total industry output for 1965 and 2010.

3.3. Drivers of change

The life cycle impact assessment results show that poultry meat production in 2010 was associated with fewer impacts across the suite of impact categories. While it is clear that background systems, rations, and bird performance had a contributing effect, further analysis is required to define the relative contribution of each. In order to determine impact changes attributable to each area, a contribution analysis was conducted. Fig. 4 shows the results of the contribution analysis for each of the impact categories under consideration.

3.3.1. Bird performance

We did not distinguish between the effects of improved genetics, nutritional advances and operational improvements like temperature regulation. Modeling the complex interactions between these attributes of poultry production were considered beyond the scope of this assessment. Instead we assumed bird performance to mean any changes in operations, breeding, or nutrition that contribute to the differences between the reference years. While each of these factors played a role in improving the efficiency of poultry meat production, previous research has shown genetics to be responsible for 85–90% of the change during a similar period of time (Zuidhof et al., 2014). We found that bird performance had a positive contribution to all of the impact categories under consideration, ranging from 12.6% (agricultural land-use) to 91.7% (acidification) of the observed difference between the two reference years. The positive influence from bird performance is not surprising, considering the lower mortality rates and higher FCRs in 2010 hens and broilers, which equate to more live weight produced with less feed consumed. The overwhelming contribution from bird performance on acidification potential is also to be expected. To demonstrate, the LCIA results showed that acidification impacts were primarily driven by live poultry production; thus, improvements in bird performance were the primary drivers of the change in that category from 1965 to 2010.

3.3.2. Background systems

Contribution analysis results suggest the 2010 background systems had a positive impact on the production of poultry meat for all categories. The largest improvement was seen in agricultural land occupation, which benefited from the dramatically improved yields of corn, wheat and soybeans. Fossil energy use and GWP improvements were primarily a result of the 2010 crop subsystems as well, but changes in the electricity grid played a role with a decreased reliance on coal and a greater contribution from renewable energy sources. The influence from background systems on acidification and eutrophication was not as great as in the aforementioned categories, but nonetheless contributed to the improvement over 1965. The relatively smaller contribution to improvement in acidification and eutrophication potentials from the background systems was not surprising based on the LCIA results of the primary crops fed to poultry. Those results were mixed (see Fig. 2), but the corn-dominated feed rations helped facilitate a net-positive contribution from the crop subsystems. The contribution from background systems to the overall change in water use was a similar story. Crop water use results were mixed between 1965 and 2010, but the dramatic decrease in water use associated with wheat production was enough to help move the net contribution from background systems to positively influence the category.

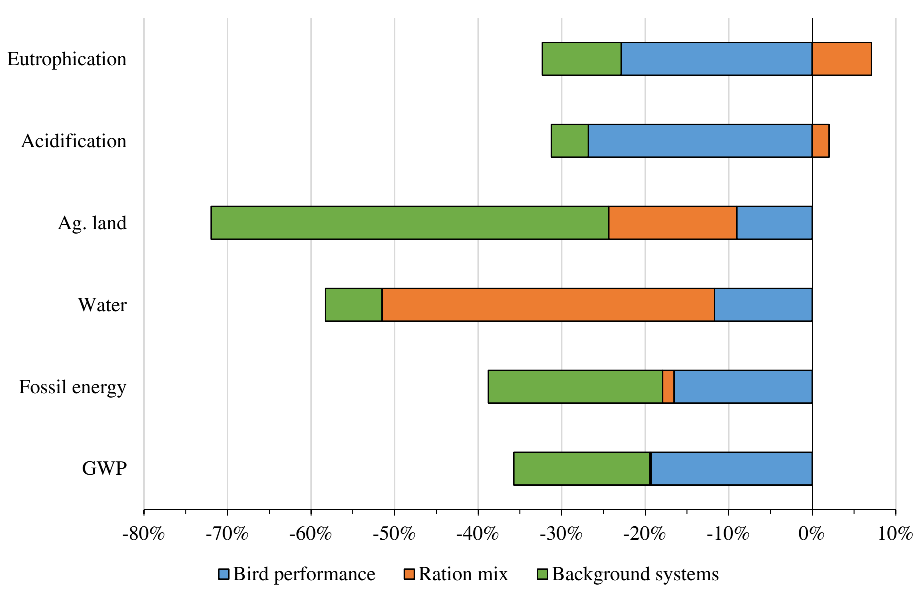

Fig. 4. Contribution to the change in impact from 1965 to 2010 for 1000 kg of LW poultry meat. The x-axis represents 1965 impact-levels.

3.3.3. Rations

In order to estimate the contribution from ration constituents, we set the 2010 ration composition to the 1965 model. Notably, our poultry growth models did not account for differences in supplied nutrition, and therefore only the impacts arising from differences in the compositions of the 2010 rations were observed by this scenario. Results from the ration analysis indicated positive and negative contributions, ranging from −28% to 68% of the observed difference between 1965 and 2010. The negative influence on acidification and eutrophication was driven by the shift towards corn and away from wheat in the 2010 ration mix. Corn produced in 1965 was associated with higher acidifying and eutrophying emissions than wheat, which resulted in a negative influence from ration compositions on the acidification and eutrophication potentials of the functional unit. Said another way, assuming all else equal, implementing the 2010 poultry ration in the 1965 model has the potential to increase acidification and eutrophication in the production of poultry meat. The ration analysis showed the opposite effect on land, water, and fossil energy use. In 1965, corn required less land, water, and fuel to produce one ton of dry matter than to produce the same amount of wheat, which resulted in a positive influence from ration compositions on the results of all three resource-related impact categories. The ration mix contribution to improvements in GWP were positive, yet minor (0.3%). The difference in emissions affecting that category were nearly offset as corn was associated with more nitrous oxide emissions from nitrogen fertilizers than wheat, but fewer from crop residues.

3.4. Sensitivity analysis

We ran our model with alternate scenarios for the treatment of poultry litter in order to determine the sensitivity of the results to our litter treatment methodology. In each scenario, litter was strictly treated as either a coproduct, as a residual, or as a waste and then compared to the distribution of classifications used in this study in order to highlight the influence of litter allocation procedures on the impacts associated with the production of the functional unit. Figs. 5 and 6 show the results of the sensitivity analysis for 1965 and 2010 production, respectively. A head-to-head Monte Carlo comparison was conducted, suggesting alternate litter treatment methods affected both years similarly; therefore, our chosen method does not unfairly bias the comparative results.

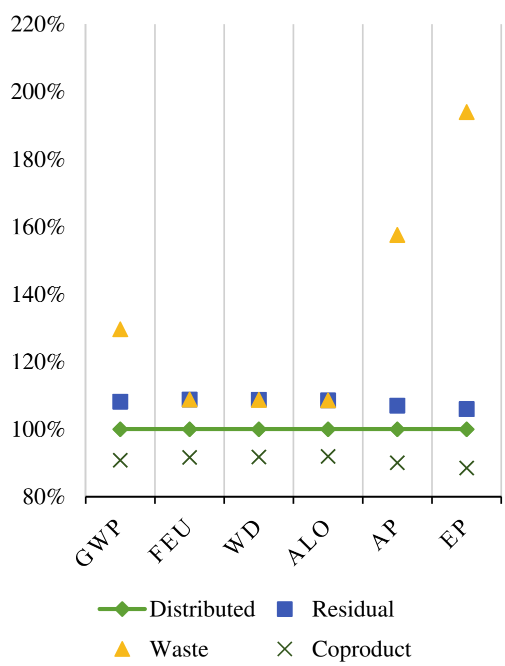

Fig. 5. Sensitivity analysis results for 1000 kg of LW poultry produced in 1965. The solid blue line labeled "Distributed" represents the baseline scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

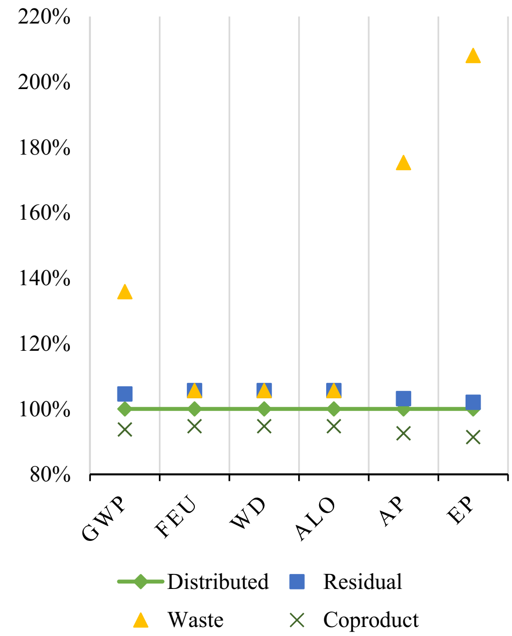

Fig. 6. Sensitivity analysis results for 1000 kg of LW poultry produced in 2010. The solid blue line labeled "Distributed" represents the baseline scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As expected, classifying 100% of litter as a coproduct lowers the LCIA result in every category in both reference years because more of the production burdens are shifted onto litter and away from the functional unit. The trend reverses with 100% classification as residual for the opposite reason, e.g. burdens are not shared by poultry litter and fall solely on the functional unit. The resource-related results are the same in both the residual and waste scenarios because litter application emissions do not affect those categories; however, the waste scenario had a dramatic effect on the emission-related categories. The increase in potential for global warming, acidification, and eutrophication in the waste scenario is a result of the continued release of nitrogen compounds from poultry litter applied to fields, and the attribution of those emissions to the functional unit.

3.5. Comparison with other studies

Previous retrospective analyses of U.S. livestock production using LCA show decreases in environmental impacts from modern production practices over their historical counterparts. To demonstrate, a study conducted on the U.S. egg industry found that acidification, eutrophication, and global warming impacts associated with egg production in 2010 fell by 65%, 71%, and 71%, respectively, as compared to 1960 (Pelletier et al., 2014). Similarly, our study found that changes in poultry production over time have resulted in lower impacts, but the magnitude of improvement was not quite as large (25–36%). There are several possible explanations for this discrepancy. Clearly, this study and that of Pelletier et al. have differing reference years and functional units; however, our LCI data show some animal-related improvements in the breeding generations are greater than their broiler generation counterparts. For example, in our study the FCR of hens in the parent generation improved by 32% from 1965 to 2010, whereas broiler FCR only improved 19%. The improvements of breeding generations are overshadowed by the broiler generation, which has a greater influence on the functional unit. Additionally, the characteristics of hens laying

Table 13
LCIA results from this study and other recent poultry LCAs. The functional unit is 1000 kg LW broiler at the farm gate unless otherwise noted.

Country	Year	Energy Use (MJ)	GWP (kg CO2 eq.)	Acidification (kg SO2 eq.)	Eutrophication (kg PO4 eq.)	Land occupation (m2a)	Water depletion (m3)
US[a]	2006	14,959	1395	15.8	3.9	–	–
FR[b]	2010	19,100	2220	28.7	13.8	6617	–
BRA[b]	2010	18,000	2060	31.4	14	3603	–
US[c]	2012	–	–	–	–	–	187
DEN[d]	2011	–	1810	–	–	–	–
UK[e]	2012	17,759	3087	32.725	14.217	3920	3.087
FR[f]	2009	12,790	2015	33.9	12.77	2687	–
UK[g]	2006	8400	3199	121.1	34.3	4480	–
US[h]	2010	12,170	1239	44.4	16.48	3054	109.6

[a] Pelletier (2008).
[b] da Silva et al. (2014).
[c] Mekonnen and Hoekstra (2012). Value represents blue water footprint for industrial chicken meat.
[d] Nielsen et al. (2011).
[e] Leinonen et al. (2012). Water depletion only considers water use on farm.
[f] Koch and Salou (2015).
[g] Williams et al. (2006). Average values for UK poultry industry, 80% chicken.
[h] This study.

eggs for consumption differ from broiler breeding hens and the methodological choices in the egg retrospective do not exactly align with ours, both of which are also likely contributors to the discrepancy.

The only LCA study covering poultry meat in the United States (Pelletier, 2008) did not include spent hen meat. For the purposes of comparison, we ran our 2010 model without spent hen meat by way of biophysical allocation and found similar values for GWP (1239 kg CO2-eq. per 1000 kg LW broiler) as the Pelletier (2008) results (1395 kg CO2-eq. per 1000 kg LW broiler), but the discrepancies were much larger when comparing the acidification and eutrophication potentials with the results of this study. Pelletier reports 11 kg NH3 were emitted at the broiler farm per ton of LW broiler produced, which is similar to our findings; however, those emissions are missing from the impact assessment results of that study. Those results are presented in Table 13 alongside the findings from this study and those from recent international poultry LCAs.

Our findings are generally in agreement with the results of other poultry meat LCAs from America and Europe. The GWP of 1000 kg of LW broilers produced in the U.S. is the lowest of all studies compiled in Table 13, and the associated energy use and land occupation are second lowest. Acidification and eutrophication potentials are on the other end of the spectrum, with only one study from the U.K. reporting higher values. Only Mekonnen and Hoekstra (2012) reported water use that included off farm consumption such as irrigation water for crops, but that result is a characterized value, which makes for an unequal comparison with our water use result.

4. Conclusions

Results from this LCA indicate that the U.S. national production of live-weight poultry for human consumption in the year 2010 has lower associated impacts than live-weight poultry produced in the year 1965. Our analysis indicates that this conclusion is not affected by data uncertainty or the attribution procedures regarding emissions from poultry litter application. Changes in poultry production from 1965 to 2010 that influenced bird performance had a positive contribution on all impact categories considered for this assessment, as did changes outside of the direct control of the poultry industry as illustrated by the positive contribution from background systems. The different rations constituents revealed mixed contributions. Despite significant improvements in each of the impact categories covered by this assessment, we found that a substantial growth in live poultry production between 1965 and 2010 caused the total industry footprint to increase over that time period.

Continued improvements to bird performance will help lower the environmental impacts associated with poultry production, although further research is required to identify which aspects of production, i.e. genetics, nutrition, etc., will produce the best results. Further work is being done at the University of Arkansas to develop a poultry production calculator that will be capable of isolating the individual contributions of these production aspects. Additional impact reductions could be gained by optimizing feed rations to minimize environmental impacts while delivering a similar nutrient profile. This approach has been shown to be successful in lowering eutrophication and global warming potentials by 1–8% and 1–12% respectively, but increased the cost by 2–8% (Nguyen et al., 2012) and material.

Prior to completion of this LCA, no retrospective analysis of poultry meat production in the United States had been completed, and no other U.S. poultry LCA incorporated hen meat for human consumption, which is produced as a result of raising broilers, into an analysis of broiler production. This methodological consideration, in addition to the inclusion of successive breeding generations, provides greater insight into the impacts associated with U.S. poultry supply chains than was previously available, which will allow the U.S. poultry industry to make more informed decisions regarding an effective sustainability strategy and will increase publicly-available LCI data with contributions to the National Agricultural Library's LCA Commons.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2017.07.008.

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