Broiler Production System Life Cycle Assessment: 2020 Update

ABSTRACT

We have quantified the environmental impact of broiler production across a range of impact categories using life cycle assessment (LCA). Our analysis shows that the broiler production sector has made significant improvements in sustainability intensity metrics (environmental footprints) between 2010 and 2020 with reductions in land use (-13%), global warming (-18%), water consumption (-13%), fossil resource scarcity (-22%) and particulate matter formation (-14%). Over the same time period, live weight broiler production increased 21% in the U.S., resulting in a cumulative increase in land use, water consumption and particulate matter impacts. Despite the growth in total production, the industry's total cumulative impact declined in the other two categories assessed (global warming and fossil resource scarcity).

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Broiler Production System Life Cycle Assessment: 2020 Update

Introduction

The NCC has commissioned an updated sustainability assessment of U.S. broiler production to better reflect current production systems. To this end, we adapted the broiler production model from Putman et al. (2017) with new life cycle inventory data to give an updated impact assessment. We account for the main poultry sector factors influencing the environmental performance of U.S. broiler production. The retrospective study by Putman et al. (2017) showed that for climate change and fossil energy consumption, approximately 50% of the improvement between 1965 and 2010 was due to broiler performance and approximately 50% of the improvement was attributed to improvements in background systems (e.g., electricity grid and transportation infrastructure). Land use and water use improvements were driven primarily by crop yield increases and by ration formulation less reliant on irrigated crops, respectively. The goal of this assessment was not an exhaustive evaluation of the many factors affecting the impact changes but is an effort to focus on the sector's primary levers of sustainability: (1) feed conversion ratio and average daily gain (including typical market live weight), (2) feed composition (industry average ration formulation), and (3) litter production and management.

Methodology

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. There are four main phases involved in conducting a LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation. The interpretation step is conducted throughout, creating the iterative nature of LCA.

Putman et al. (2017) presented a retrospective assessment of broiler production from 1965 through 2010. They showed significant improvements in numerous sustainability metrics over that time frame driven by a variety of factors. Their study determined the most significant factors driving continual improvement were feed conversion (or broadly, animal performance) and overall improvements in the efficiency of the economy (fuel efficiency and crop yields, for example). The diagram in Figure 1 (below) illustrates the system boundaries and lifecycle stages included in the retrospective study, which have been adopted for the current update (Note that while the system structure is the same, not all the inventory data were available for update.)

This update builds upon the modeling framework established in the retrospective study with updates to key elements that more accurately represent the conditions of 2020. The national aggregated data received from Agri-Stats included production information from 2010 in addition to 2020. To provide an 'apples-to-apples' comparison between 2010 and 2020, we updated the 2010 version of the retrospective model with the 2010 production data from Agri-Stats. This adaptation minimizes complications that could arise from mixed data sources, including intervening updates to standard LCA databases, and mixed data quality.

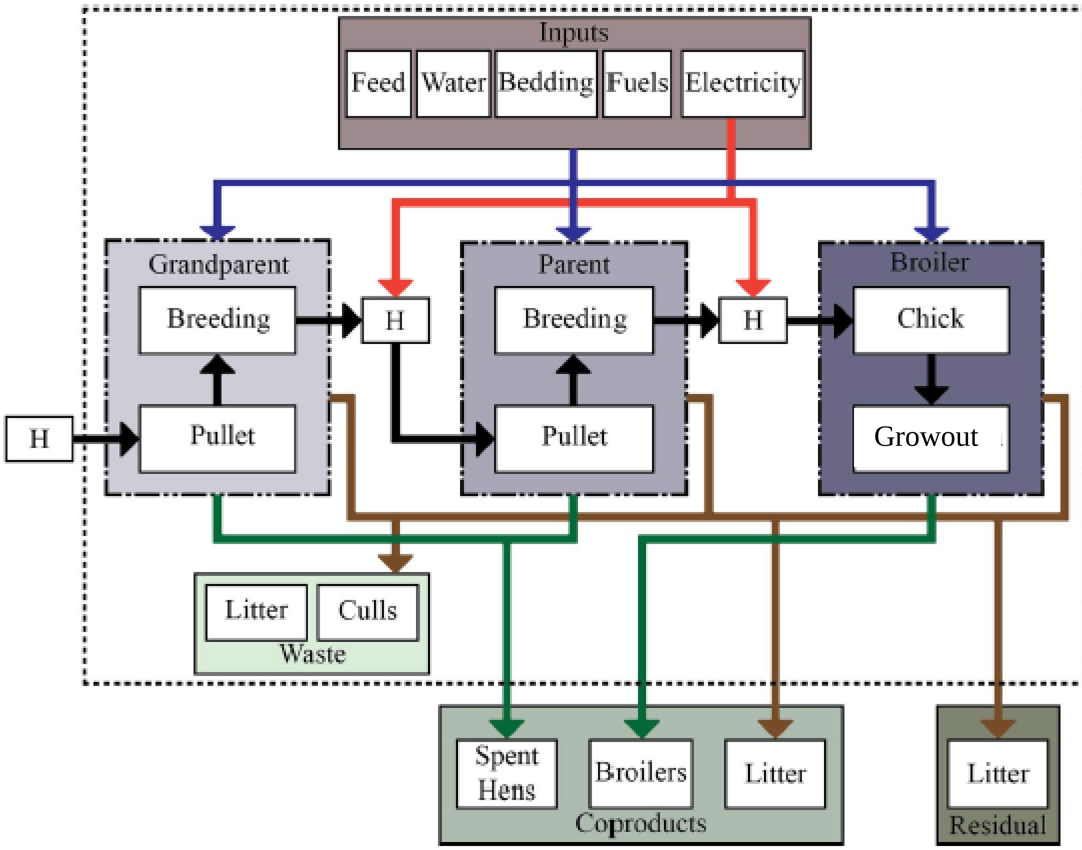

Figure 1. Broiler production system model. [H] represents hatcheries. Background system inputs are shown at the top and outputs and emissions at the bottom of the diagram. Figure copied from Putman et al. (2017).

Although we had initially planned to compare the 2020 data to the data in the published paper, we realized that direct comparisons (without considering the 2010 data updates included in this report) would have been misleading. For example, among the important updates to the 2010 inventory (data) is the addition of dried distillers' grains to the broiler rations. The retrospective study did not include distillers' grains, meaning that the updated Agri-Stats data for 2010 provides a more representative picture of the rations consumed at that time and therefore, a more representative comparison to 2020.

In addition to the data provided by Agri-Stats, we supplemented the lifecycle inventory with other publicly available data. Data on litter production and management is generally not available, and we relied on our prior methodology. We chose not to seek additional expert opinion beyond that provided directly from NCC and Agri-Stats, because the primary missing information was regarding litter and litter management. As shown in the discussion, and despite an initial assessment of its importance, litter management does not represent a significant contributing factor to impacts.

Litter management data was derived from a combination of sources. The amount of bedding material required per bird as well as the expected amount of excreta per kg feed consumed were based on recommendations from Leeson and Summers (2009), and the economics and frequency behind litter removal was informed by a publication from McDonald (2014). Nitrogen content in litter and management-related emissions were calculated using standard emission factors from the IPCC (Dong et al., 2006).

We followed the LEAP guidelines regarding the allocation of environmental burdens to manure (LEAP, 2015). The LEAP guidelines define three alternate options for accounting for litter emissions. These are residual, co-product, and waste. We estimated the fraction of the national litter stock which can be classified as each of these, as shown in Table 1 below. The residual classification assigns off-farm emissions to the off-farm activity, typically crop production. The co-product classification provides a mechanism where some of the emissions from animal husbandry are assigned to the litter, thus both a fraction of the animal husbandry emissions as well as the field emissions from subsequent land application would be assigned to the crop. The waste classification requires that emissions from off-farm management of litter are assigned back to the animal husbandry stage. 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. We did not update these factors for the 2020 evaluation.

Table 1.The nature of transactions regarding poultry litter disposal in the U.S. and their consequences on output classification according to LEAP guidelines.

Disposal transaction	Fraction of litter from		Classification
	Broilers	Breeders	
Sold	50%	36.3%	Co-product
Hauled off for a fee	3.2%	4.2%	Waste
Bartered	36.1%	39%	Residual
Given away	10.7%	20.5%	Residual

Updated data

Agri-Stats provided aggregated, national-level data covering much of the feed consumption, energy use, and production characteristics of the poultry sector to support a high-level update to the sector’s footprint (Table 2). The data from Agri-Stats included a detailed breakdown of the primary feed ingredients and quantities consumed in the U.S. poultry sector for 2010 and 2020. It included feed during broiler production, in addition to rearing pullets and breeding hens. The table presents data for both broiler production and culled breeder hens. It is assumed that the culled hens enter the human food supply chain and are therefore combined with the broilers to create a representative “average” bird for slaughter. The information is reported in both metric and imperial units. These data were adapted and imported into the OpenLCA computational platform to perform the lifecycle impact assessment.

Supplemental feeds

Agri-Stats provided a detailed ingredient list for feeds in different production stages. However, approximately 8% and 14% of the total ration was not identified for broilers and breeders, respectively.

To address this gap, we adopted the supplements, shown in Table 3, based on the work of Putman et al. (2017). These ingredients were added to match the total feed consumption reported in Table 2.

Table 2. Aggregated National Statistics from Agri-Stats.

Benchmarking Item	2010	2020	Percent change
U.S. Broilers (number)	8,447,107,031	9,229,819,998	9.3%
Broiler Production (kg) *[lb]*	21,993,058,529 *[48,486,394,357]*	26,668,488,658 *[58,793,953,386]*	21.3%
Broiler Feed Consumed (tonne)	47,516,666	52,620,588	10.7%
Broiler Live Weight (kg) *[lb]*	2.603 *[5.74]*	2.889 *[6.37]*	11.0%
Average Broiler FCR	1.96	1.79	-8.7%
Cull Breeder Hens (number)	61,519,743	66,257,127	7.7%
Cull Breeder Hen Production (kg) *[lb]*	189,327,008 *[417,394,605]*	203,906,309 *[449,536,462]*	7.7%
Hen Feed Consumed (tonne)	2,712,840	2,889,737	6.5%
Hen Live Weight** (kg) *[lb]*	3.08 [6.79]	3a [6.79]	0.0%
"Average" bird for slaughter (kg) *[lb]*	2.607 *[5.748]*	2.891 *[6.373]*	10.9%

** Spent hen weight adopted from Putman et al. (2017); new data was not available.

Table 3. Supplemental feeds that were not reported in Agri-Stats data.

Feed ingredient	Broiler ration supplements (8% of broiler ration)	Feed ingredient	Hen ration supplements (14% of hen ration)
Meat and bone meal	5.0%	Limestone	7.4%
Limestone	1.0%	Meat and bone meal	4.7%
Tallow	1.5%	Tallow	1.6%
Di-calcium phosphate	0.2%	Di-calcium phosphate	0.1%
Salt	0.2%	Salt	0.2%
Vita-Min mix	0.1%	DL-Methionine	0.1%
		Hen vitamin mix	0.1%
Total	8.0%		14.2%

Life cycle impact assessment

We utilized the ReCiPe lifecycle impact assessment framework (Huijbregts et al., 2016), which is an internationally recognized and widely used set of characterization factors which are used to translate lifecycle inventory emissions into impact categories (a subset of these categories is presented in Table 4 and a full description of all categories is given in the Appendix). For example, the climate change impact category is computed using global warming potential (GWP) that have been published by the Intergovernmental Panel on Climate Change (IPCC) based on the differences in radiative forcing of various greenhouse gases coupled with their expected atmospheric lifetimes. In the most recent update from IPCC, biogenic methane (emitted from some litter management techniques) is characterized as having 34 times the global warming potential of carbon dioxide; thus, its characterization factor is 34 kg CO_2e per kilogram CH_4 (Myhre et al., 2013).

Table 4. List of primary environmental impact categories from ReCiPe.

Resource/impact categories	**Units**	**Definitions**
Climate change	kg CO_{2eq}	IPCC GWP100a: Global Warming Potential of the GHG emissions are based on a 100-year time horizon with climate-carbon feedback (Myhre et al., 2013).
Land use	$m^2 crop_{eq}$	Land use helps to assess how land use and land-use change affect biodiversity (Huijbregts et al., 2017, 2016)
Fossil resources scarcity	kg oil_{eq}	This characterizes the depletion of fossil fuel resources.
Water use	m^3	Refers to water consumed unit process and thus no longer available in a watershed (Huijbregts et al., 2016)
Fine particulate matter formation	kg $PM2.5_{eq}$	Disease incidence due to kg of PM2.5 emitted. This refers to particulates that are 2.5 µm and smaller. This is primarily a result of ammonia emissions.

Results

Figure 2 presents the side-by-side comparison for the five primary impact categories of primary interest for this update. We have performed a Monte Carlo simulation and used bootstrap statistics to characterize the likelihood that the impacts for 2020 and 2010 are different. In each case, we find that the 2020 impacts are lower than the 2010 impacts ($p < 0.0001$). We report life cycle impact assessment (LCIA) on five primary impact categories in the main body of this report and provide a complete profile of the 18 categories from the ReCiPe impact assessment method in the Appendix.

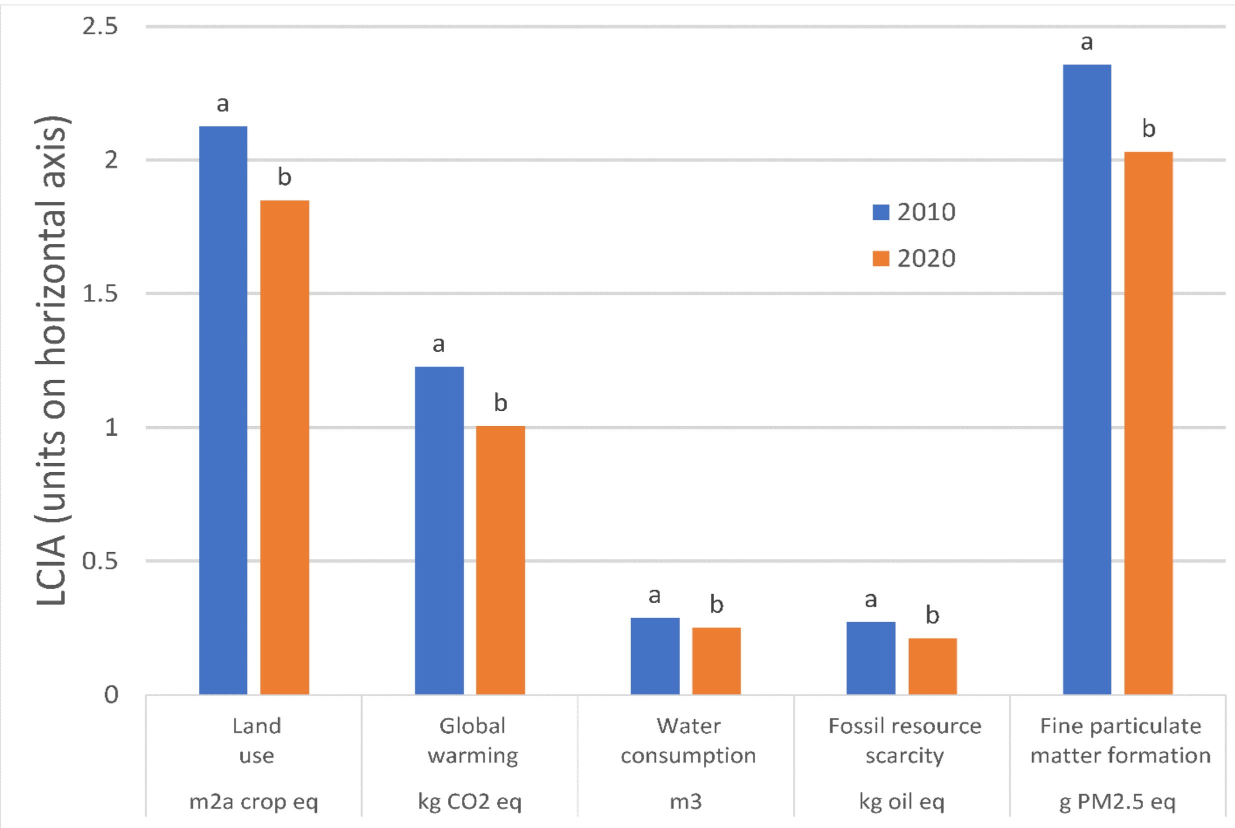

Figure 2. Comparison of 2010 and 2020 of the five principal environmental impacts per kg live weight (broiler plus culled breeder hens) for harvest. Within each impact category, columns with different letters are significantly different (p<0.0001). Note units for PM2.5 are grams, not kilograms.

Figure 3 and Figure 4 present the percentage contribution for carbon footprint. In both figures the functional unit is live weight of broiler plus culled breeder hen ready for slaughter. In each of these figures, the left most node represents the functional unit of 1 kg of live weight ready for slaughter. The branches then show percentage contribution of each of designated flows as a fraction of the total greenhouse gas emissions or carbon footprint. We can note that there is an approximately 94:6 distribution of greenhouse gas emissions between broiler production and breeders in terms of direct contribution to the live weight total. We note, separately, that approximately 1% of the total live weight is attributed to culled hens associated with allocation of breeder operation emissions between eggs and culled hens. The baby chicks' contribution to the broiler branch accounts for both the production of

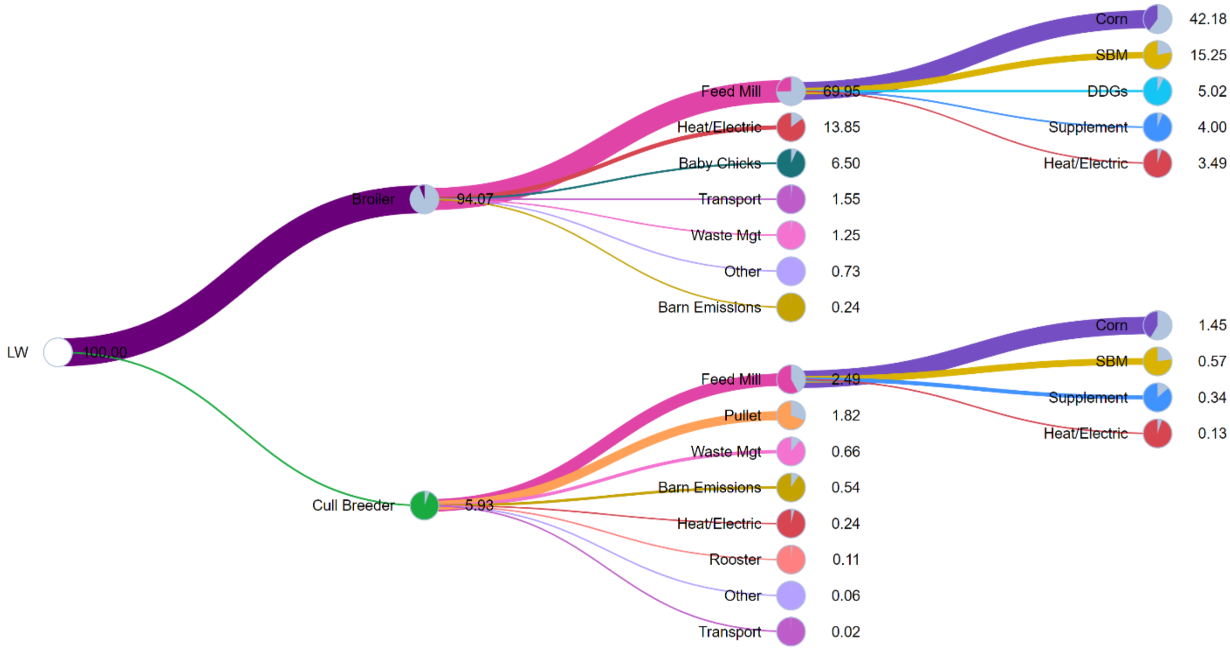

Figure 3. Climate change contribution tree for 2020. Values reported as percentage.

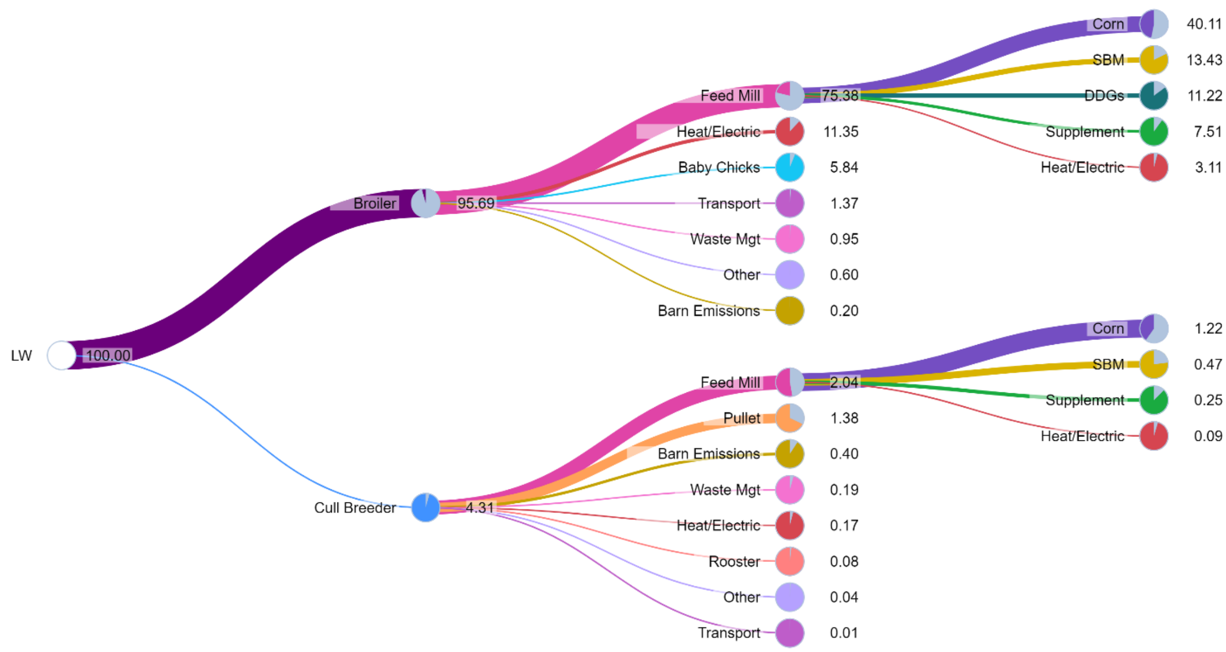

Figure 4. Climate change contribution tree for 2010. Values reported as percentage.

hatching eggs and hatchery operation. A notable feature of this pair of charts is the dominating contribution of feed, approximately 77% of the total in 2010 and 72% of total 2020. The notable decrease in the fractional contribution of feed at the broiler stage in 2020 compared to 2010 is driven significantly by decreased consumption of distillers' grains in 2020.

Table 5 presents the five primary categories, demonstrating between 13 and 22% decrease in each intensity metric between 2010 and 2020. Notably the carbon footprint has decreased 18%. This reduction is driven by a combination of factors. Two main factors accounted for in this update are the 8.7% improvement in feed conversion ratio (enabling a 21% increase in production with only 11% increase in feed consumed) and a decrease of distillers' grains in the broiler ration. Distillers' grains have a larger carbon footprint than corn and soy because of the drying energy used at ethanol biorefineries.

Table 5. Percentage change in intensity measures of the five principal impact categories between 2010 and 2020: functional unit of 1 kg of LW (broiler plus cull breeder hen). Parenthetical values are per "average" bird as defined in Table 2.

Impact category	2010	2020	Percent change
Land use (m^2a crop eq)	2.13 (5.54)	1.85 (5.26)	-13.0% (-3.5 %)
Global warming (kg CO_2 eq)	1.23 (3.20)	1.00 (2.90)	-18.1% (-9.2%)
Water consumption (m^3)	0.29 (0.75)	0.25 (0.73)	-13.0% (-3 %)
Fossil resource scarcity (kg oil eq)	0.27 (0.71)	0.21 (0.61)	-22.1% (-13.7%)
Fine particulate matter formation (g PM2.5 eq)	2.36 (6.14)	2.03 (5.87)	-13.8% (-4.5%)

While reduction in intensity metrics is extremely important, it does not tell the complete story. For example, climate change is only a function of the cumulative emissions of greenhouse gases across all sectors, globally. Thus, the complete view of climate change (and similarly for other categories) for broiler production must include an accounting of the cumulative emissions which are determined from the intensity metrics discussed above (in Table 5) and the total production quantity from the sector (Table 2). Table 6 presents the cumulative change in emissions between 2010 and 2020 for the five main impact categories in this report. The Appendix includes a complete suite of the ReCiPe impact method. While there are decreases for some of the cumulative impacts, most notably for resource use and climate change, other categories showed an increase. Overall, this is a very promising trend because it is often the case that growth of a sector outpaces the improvement in intensity.

Limitations

It is tempting to make direct comparisons of the 2010 values reported in this update against those reported in the 2017 retrospective paper Putman et al. (2017). However, as mentioned above, there are differences in the data sources and differences in the background databases used to simulate production of fertilizers and fuels consumed.

Table 6. Percentage change in five principal impact categories between 2010 and 2020: sector level total production (broiler plus cull breeder hen).

Impact category	2010	2020	Percent change
Land use (m^2a crop eq)	47,157,854,711	49,701,161,527	5.4%
Global warming (kg CO_2 eq)	27,225,935,616	27,000,732,155	-0.8%
Water consumption (m^3)	6,401,558,672	6,748,789,920	5.4%
Fossil resource scarcity (kg oil eq)	6,035,302,938	5,691,972,956	-5.7%
Fine particulate matter formation (kg PM2.5 eq)	52,283,488	54,568,949	4.4%

In this report, we have made every effort to provide an accurate comparison between 2010 and 2020 based on common data sets with comparable data quality and approximate representativeness. Three main driving factors affecting the current simulated 2010 sustainability metrics are the feed ration, feed conversion ratio, and changes in crop yield. These three factors were adjusted in the 2010 lifecycle inventory model to match data provided by Agri-Stats and Quick Stats from the NASS for yield of corn and soy in 2010 and 2020, respectively.

A more thorough approach would require updating background processes, which was beyond the scope of this report. Such updates would address changes in farm equipment and transportation fleet efficiency, to represent then-current fuel efficiencies. In addition, process updates would cover changes in the electric grid during the past decade, reflecting the shift from coal to natural gas and renewables. Without these types of modifications, we believe that the reported numerical results are slightly more favorable than the actual conditions in 2010-because the background database for transportation and other activities is based on 2020 conditions. However, as discussed, these factors are relatively small contributions to the overall metrics. Therefore, we have high confidence in the fractional improvement in impacts reported between 2010 and 2020.

Data quality assessment

The major updates in this report are derived from information provided by Agri-Stats, which is considered to have very high quality due to the origin of the information provided to Agri-Stats. Some of the data used in this assessment (specifically related to waste management) were adopted from the 2017 retrospective study and thus have slightly lower data quality than the primary data regarding feed consumption and conversion. However, as seen from the contribution charts, waste management contributes less than approximately 2% of greenhouse gas emissions, thus lower data quality for these contributions is very unlikely to affect the conclusions of this study.

Conclusions

All the intensity metrics from the ReCiPe framework showed significant improvement over the past decade driven by a combination of factors. The primary drivers, as mentioned, include improvement in feed conversion ratio and a shift in ration formulation away from dried distillers' grains. The contribution analysis corroborates previous studies in which the production and consumption of feed in the poultry supply chain is the dominant contributing factor to climate change impacts, representing approximately 70% of total climate change impacts reported as carbon dioxide equivalent. The carbon footprint intensity reduced by approximately 18% between 2010 and 2020. However, as shown in the Appendix, because of increased total production, the sectors' cumulative emissions of greenhouse gases reduced by only about 0.8%. Further, the uniform reductions observed in intensity metrics are not translated directly into uniform reductions for the entire broiler sector, as shown in the data presented in the Appendix.

Recommendations

This update provides insight into the recent gains made in terms of environmental sustainability. However, the underlying data have been aggregated at national scale and this precludes the opportunity of identifying specific management practices which may be more beneficial. In addition, there may be regional differences which would be valuable to understand in the context of establishing directions for the industry. It is clear that given the contribution analysis from Figures 3 and 4 that factors affecting feed consumption are of paramount importance as the industry looks to the future and considers establishing reduction targets. Thus, efforts focused on continual improvement in feed conversion ratio remain important. These might include ongoing efforts at improvement to genetics of the animals or evaluation of feed additives and supplements that might impact feed conversion. External factors which will likely contribute to improvement of the industry footprints are associated with increasing the yield and crop production, improved fuel efficiency in the transportation and distribution truck fleets and increasing adoption of renewable energy sources to replace fossil energy sources in the supply chain.

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Appendix: Life cycle inventory mode and comprehensive life cycle impact assessment results

Lifecycle inventory

In this Appendix, we present lifecycle inventory data for some of the major contributing activities in the supply chain focusing on broiler and breeder operations. Table 7 presents the lifecycle inventory model for broiler production based on one broiler produced with a live weight of 6.37 pounds (industry average reported from Agri-Stats). Table 8 presents the lifecycle inventory data for breeder production with a reference flow of one hatching egg for delivery to a hatchery with a weight of 60 g (assumed typical weight).

Interpreting the table: for example, 1.053 baby chicks are needed for each broiler produced to account for mortality. The broiler operation consumes the inputs and produces (or emits) the outputs.

Table 7. 2020 broiler operation lifecycle inventory flows. Reference flow is one broiler with a live weight of 6.37 pounds.

Inputs

Flow	Amount	Unit
baby chicks	1.053	Item(s)
diesel, burned in diesel-electric generating set	0.235	MJ
electricity, medium voltage	0.251	kWh
heat, district or industrial, propane	3.336	MJ
milled feed	11.40	lb
poultry mortalities	0.168	lb
transport, freight, lorry >32 metric ton	0.541	t*km
shavings, softwood, loose, measured as dry mass	0.211	kg

Outputs/emissions

Flow	Amount	Unit
One broiler (live weight produced)	***6.37***	***lb***
ammonia	1.09	g
dinitrogen monoxide (nitrous oxide)	0.018	kg
methane, non-fossil	0.058	kg
poultry litter; from broilers	1.38	kg

Table 8. 2020 breeder operation lifecycle inventory flows. Reference flow is one 60 g hatching egg.

Inputs

Flow	Amount	Unit
milled feed	253.6	g
pullets	0.00632	Item(s)
roosters	0.00063	Item(s)
diesel, burned in diesel-electric generating	0.0241	MJ
electricity, medium voltage	0.0179	kWh
heat, district or industrial, propane	0.0003	MJ
poultry mortalities	1.95	g
transport, freight, lorry >32 metric ton	9.173	kg*km
shavings, softwood, loose, measured as dry mass	0.417	kg
tap water	507	g

Outputs/emissions

Flow	Amount	Unit
hatching eggs	***1***	***Item(s)***
culled hens	17.9	g
poultry litter; from broiler breeder hens	67.6	g
ammonia	2.86	g
dinitrogen monoxide (nitrous oxide)	0.053	g
methane, non-fossil	0.190	g

Lifecycle impact assessment

Table 9 provides a description of the 18 impact assessment categories from the ReCiPe method. Figure 5 and Figure 6 present the comparison of environmental impact across the 18 categories. Table 10 summarizes the major activities and emissions associated with each impact category.

It is noteworthy that many of the impact assessment categories are associated with upstream activities such as fossil fuel and resource extraction and electricity generation. Opportunities for mitigating these impacts arise primarily in the efforts to reduce consumption in the sector. For example, shifting from fossil-based electricity to renewable energy would have notable benefits through reduction of upstream impacts arising from mining in electricity production. Increasing efficiency of the transportation sector and agricultural machinery will lead to reduction in combustion related emissions and the associated impacts.

Table 9. List of environmental impact categories from ReCiPe.

Resource/impact/damage categories	Units	Definitions
Climate change	kg CO_{2eq}	IPCC GWP100a: Global Warming Potential of the GHG emissions are based on a 100-year time horizon with climate-carbon feedback (Myhre et al., 2013).
Land use	m^2crop_{eq}	Land use helps to assess how land use and land-use change affect biodiversity (Huijbregts et al., 2017, 2016)
Fossil resources scarcity	kg oil_{eq}	This characterizes the depletion of fossil fuel resources.
Mineral resource scarcity	kg Cu_{eq}	This represents the depletion of mineral resources.
Water use	m^3	Refers to water consumed unit process and thus no longer available in a watershed (Huijbregts et al., 2016)
Terrestrial acidification	kg SO_{2eq}	Change in acidity in the soil due to the atmospheric deposition of sulfates, nitrates, and phosphates. Major acidifying substances are NO_X, NH_3, and SO_2. (Huijbregts et al., 2016).
Freshwater eutrophication	kg_P_{eq}	This factor expresses the increase in phosphorus mass per kg P discharged to aquatic environments.
Marine eutrophication	kg N_{eq}	Expressed as the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as the limiting factor in marine water).
Freshwater ecotoxicity	[a]1,4DCB_{eq}	Aquatic toxicity the effect of a chemical substance to aquatic species which is usually determined on organisms representing the three trophic levels, i.e., vertebrates (fish), invertebrates (crustaceans as Daphnia) and plants (algae) (Huijbregts et al., 2017).
Terrestrial ecotoxicity	1,4DCB_{eq}	Estimated based on acute toxicity data (E.C. 50s)
Fine particulate matter formation	kg $PM2.5_{eq}$	Disease incidence due to kg of PM2.5 emitted. This refers to particulates that are 2.5 µm and smaller.
Human toxicity (Carcinogens)	1,4DCB_{eq}	The carcinogenic impact is based on exposure to metals and organic pollutants (Huijbregts et al., 2016)
Human toxicity (Noncarcinogens)	1,4DCB_{eq}	Non-carcinogenic effects of chemical exposure.
Marine ecotoxicity	1,4DCB_{eq}	Chemicals emitted to marine ecosystems. (Huijbregts et al., 2016)
Photochemical ozone formation	kg $NO_{x\ eq}$	Ozone is not directly emitted into the atmosphere, but it is formed because of photochemical reactions of nitrogen oxides (NOx) and Non-Methane Volatile Organic Compounds (NMVOCs). Ozone is a health hazard to humans because it can inflame airways and damage the lungs. (Huijbregts et al., 2016)
Ozone Layer Depletion	kg CFC 11_{eq}	Ozone-depleting substances emitted by human activity destroy the ozone layer in the stratosphere, which blocks UVB, by breaking ozone molecules into molecular oxygen through heterogeneous catalysis (Huijbregts et al., 2017).
[a] DCB = di-chlorobenzene; [b] SO_2 = Sulphur dioxide		

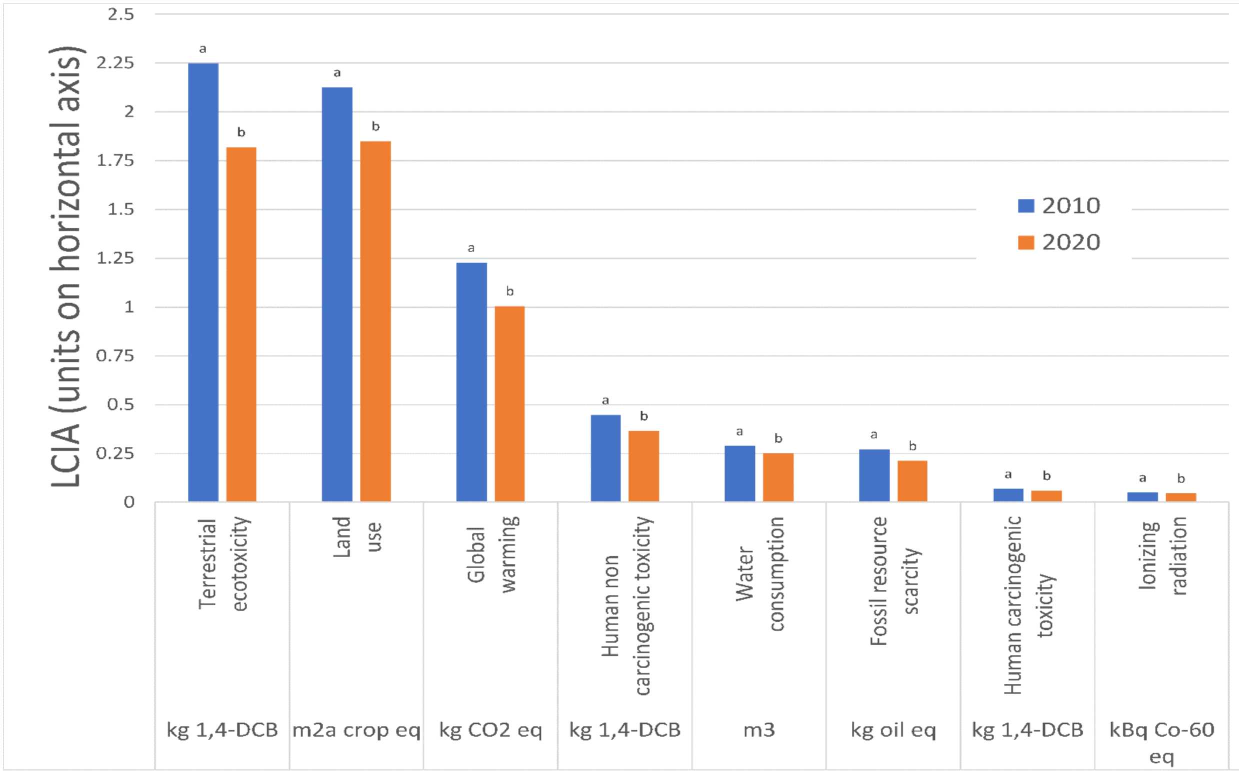

Figure 5. Select impact categories for functional unit of 1 kg LW, Broiler + Culled Breeder Hens for harvest. Columns within a category with different letter designations are significantly different ($p<0.0001$).

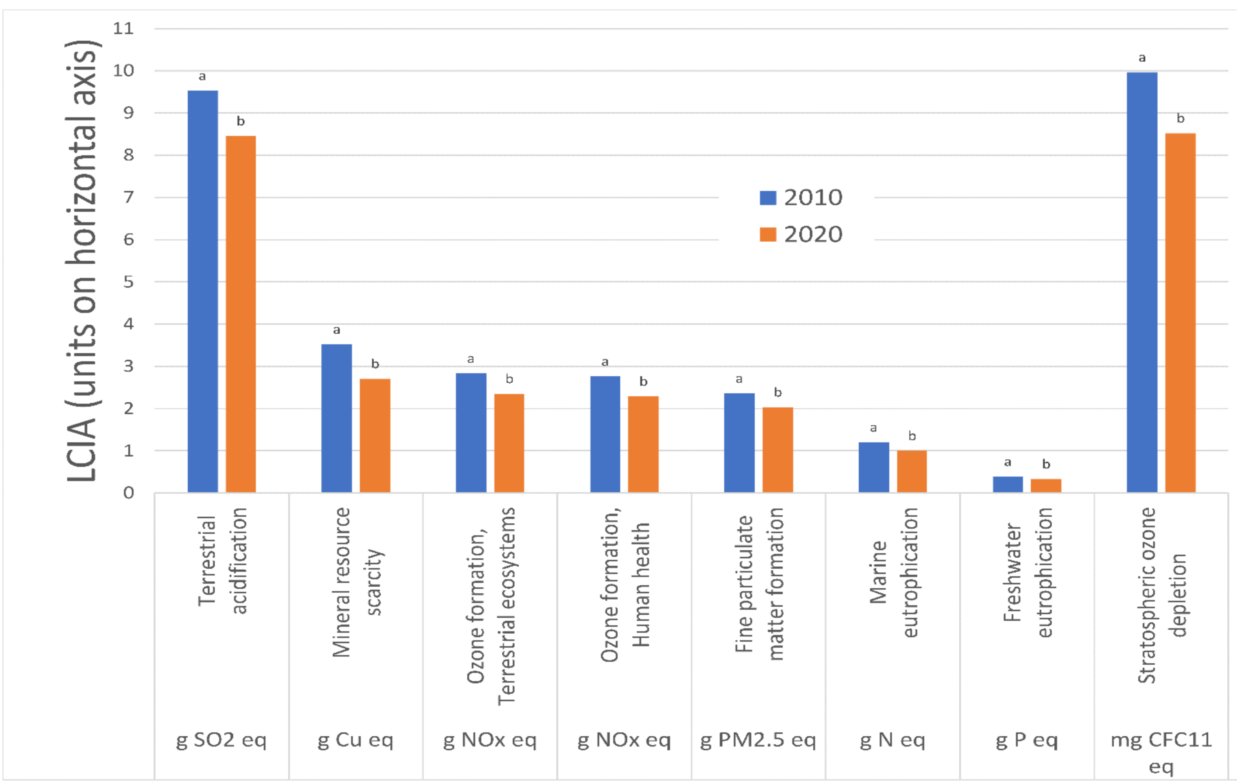

Figure 6. Remaining impact categories for functional unit of 1 kg LW, Broiler + Culled Breeder Hens for harvest. Columns within a category with different letter designations are significantly different ($p<0.0001$).

Table 10. Summary of activities and emissions contributing significantly to each impact category.

Impact category	Important activities/emissions	Impact category	Important activities/emissions
Terrestrial ecotoxicity (kg 1,4-DCB)	Brake wear emissions (transportation); pesticides	**Marine ecotoxicity (kg 1,4-DCB)**	Heavy metal emissions from mining operations
Land use (m2a crop eq)	Crop production	**Freshwater ecotoxicity (kg 1,4-DCB)**	Heavy metal emissions from mining operations
Global warming (kg CO_2 eq)	Crop production and fossil fuel combustion	**Terrestrial acidification (g SO_2 eq)**	Ammonia emissions from crop and broiler production; sulfur and nitrogen oxides from combustion
Human non-carcinogenic toxicity (kg 1,4-DCB)	Heavy metals from mining tailings	**Mineral resource scarcity (g Cu eq)**	Phosphate and metal mining
Water consumption (m^3)	Irrigation	**Ozone formation, Terrestrial ecosystems (g NOx eq)**	Nitrogen oxides and NMVOC from combustion
Fossil resource scarcity (kg oil eq)	Fossil fuel usage	**Ozone formation, Human health (g NOx eq)**	Nitrogen oxides and NMVOC from combustion
Human carcinogenic toxicity (kg 1,4-DCB)	Heavy metals and arsenic from mining tailings treatment	**Fine particulate matter formation (g PM2.5 eq)**	Ammonia and nitrogen oxides from hatchery grain production combustion and electricity generation
Ionizing radiation (kBq Co-60 eq)	Nuclear power	**Marine eutrophication (g N eq)**	Nitrate emissions from field crops
Stratospheric ozone depletion (mg CFC11 eq)	Nitrous oxide emissions from crop production and litter management	**Freshwater eutrophication (g P eq)**	Phosphorous loss from field crops and coal mining tailings

Table 11 and Table 12 present the complete suite of impact categories evaluated in this update. Table

Table 11. Percentage change in 18 impact categories between 2010 and 2020: functional unit of 1 kg of live weight (broiler plus spent hen). Parenthetical values are per "average" bird as defined in Table 2. Note units change for some categories.

Impact category	2010	2020	Percent change
Terrestrial ecotoxicity (kg 1,4-DCB)	2.25 (5.86)	1.82 (5.35)	-19.1% (-10.3 %)
Land use (m2a crop eq)	2.13 (5.54)	1.85 (5.26)	-13.0% (-3.5 %)
Global warming (kg CO_2 eq)	1.23 (3.20)	1.00 (2.90)	-18.1% (-9.2%)
Human non-carcinogenic toxicity (kg 1,4-DCB)	0.45 (1.17)	0.37 (1.06)	-18.2% (-9.3%)
Water consumption (m^3)	0.29 (0.75)	0.25 (0.73)	-13.0% (-3 %)
Fossil resource scarcity (kg oil eq)	0.27 (0.71)	0.21 (0.61)	-22.1% (-13.7%)
Human carcinogenic toxicity (kg 1,4-DCB)	0.069 (0.18)	0.059 (0.17)	-14.1% (-4.7%)
Ionizing radiation (kBq Co-60 eq)	0.051 (0.13)	0.045	-11.8% (-2.2%)
Marine ecotoxicity (kg 1,4-DCB)	0.048 (0.125)	0.039 (0.13)	-19.3% (-10.5%)
Freshwater ecotoxicity (kg 1,4-DCB)	0.041 (0.106)	0.033 (0.11)	-19.2% (-10.4%)
Terrestrial acidification (g SO_2 eq**)**	9.53 (24.8)	8.45 (24.4)	-11.3% (-1.6%)
Mineral resource scarcity (g Cu eq)	3.52 (9.17)	2.70 (7.82)	-23.2% (-14.8%)
Ozone formation, Terrestrial ecosystems (g NOx eq)	2.83 (7.38)	2.35 (6.79)	-17.1% (-8.1%)
Ozone formation, Human health (g NOx eq)	2.76 (7.20)	2.29 (6.61)	-17.2% (-8.2%)
Fine particulate matter formation (g PM2.5 eq)	2.36 (6.14)	2.03 (5.87)	-13.8% (-4.5%)
Marine eutrophication (g N eq)	1.20 (3.12)	1.00 (2.89)	-16.9% (-7.8%)
Freshwater eutrophication (g P eq)	0.39 (1.01)	0.33 (0.94)	-15.7% (-6.5%)
Stratospheric ozone depletion (mg CFC11 eq)	9.97 (26.0)	8.52 (24.6)	-14.5% (-5.2%)

Table 12. Percentage change in 18 impact categories between 2010 and 2020: sector level total production (broiler plus cull breeder hen) based on production in Table 11.

Impact category	2010	2020	Percent change
Terrestrial ecotoxicity (kg 1,4-DCB)	49,875,309,932	48,865,377,483	-2.0%
Land use (m2a crop eq)	47,157,854,711	49,701,161,527	5.4%
Global warming (kg CO_2 eq)	27,225,935,616	27,000,732,155	-0.8%
Human non-carcinogenic toxicity (kg 1,4-DCB)	9,919,467,648	9,826,999,383	-0.9%
Water consumption (m^3)	6,401,558,672	6,748,789,920	5.4%
Fossil resource scarcity (kg oil eq)	6,035,302,938	5,691,972,956	-5.7%
Human carcinogenic toxicity (kg 1,4-DCB)	1,531,279,301	1,593,580,771	4.1%
Ionizing radiation (kBq Co-60 eq)	1,127,431,021	1,204,410,507	6.8%
Marine ecotoxicity (kg 1,4-DCB)	1,062,169,317	1,039,029,355	-2.2%
Freshwater ecotoxicity (kg 1,4-DCB)	901,471,969	882,640,624	-2.1%
Terrestrial acidification (kg SO_2 eq**)**	211,371,8	227,115,4818	7.4%
Mineral resource scarcity (kg Cu eq)	78,060,830	72,666,029	-6.9%
Ozone formation, Terrestrial ecosystems (kg NOx eq)	62,836,740	63,089,217	0.4%
Ozone formation, Human health (kg NOx eq)	61,281,920	61,474,636	0.3%
Fine particulate matter formation (kg PM2.5 eq)	52,283,488	54,568,949	4.4%
Marine eutrophication (kg N eq)	26,575,691	26,754,911	0.7%
Freshwater eutrophication (kg P eq)	8,572,459	8,758,868	2.2%
Stratospheric ozone depletion (kg CFC11 eq**)**	221,072	228,902	3.5%

10 presents the results on an intensity basis, meaning the emissions in each category associated with 1 kg of live weight produced. Table 11, on the other hand, presents the cumulative impact associated with the full production reported in the respective years from Agri-Stats. While there is uniform improvement in the intensity metrics, driven by improved corn and soy yield as well as improved feed

conversion ratio for broilers and hens, the increase in production outpaced the improvement in intensity for several of the categories. A complete environmental sustainability assessment should include both intensity and cumulative impact metrics. A significant pathway for achieving a sustainable food system in the future is sustainable intensification. Sustainable intensification involves keeping pace with increases in production – to be considered fully sustainable, the improvements in intensity of emissions must keep pace with the rate of increase in overall production. The broiler sector has shown that this is an attainable target.

Monte Carlo statistical evaluation

Monte Carlo simulation involves, first, assigning a probability distribution to input inventory in the lifecycle inventory model. Sensitive inputs, including energy consumption and feed utilization were assigned uncertainty ranges of 3% of the mean value and emissions estimates, which are based on models rather than measured data were assigned a 54% uncertainty range. 200 separate simulations were performed using the open LCA software platform with a functional unit of 1 kg of live weight produced in 2020 minus 1 kg of live weight produced in 2010. The results, shown in Table 13, coupled with a boot strap statistical procedure was used to determine the statistical probability that the difference between the mean values for the two production years was zero. The statistical evaluation demonstrates that for each of the impact categories the mean intensity metric values are different from each other ($p<0.0001$). This p-statistic indicates greater than 99.99% confidence that the 2020 values are smaller than the 2010 values.

Table 13. Summary of Monte Carlo simulation results comparing 2010 and 2020 production.

Impact category	Mean*	Standard deviation	5th Percentile	95th Percentile
Terrestrial ecotoxicity (kg 1,4-DCB)	-5.3E-01	8.9E-02	-6.8E-01	-3.9E-01
Land use (m2a crop eq)	-2.7E-01	2.2E-01	-6.5E-01	7.4E-02
Global warming (kg CO_2 eq)	-2.3E-01	5.8E-02	-3.2E-01	-1.3E-01
Human non-carcinogenic toxicity (kg 1,4-DCB)	-3.6E-01	1.2E+00	-7.1E-01	-8.4E-02
Water consumption (m^3)	-3.6E-02	3.4E-02	-9.1E-02	1.7E-02
Fossil resource scarcity (kg oil eq)	-6.2E-02	7.2E-03	-7.4E-02	-5.0E-02
Human carcinogenic toxicity (kg 1,4-DCB)	-2.4E-02	4.2E-02	-5.6E-02	-8.3E-03
Ionizing radiation (kBq Co-60 eq)	-1.5E-02	3.9E-02	-5.5E-02	-1.6E-03
Marine ecotoxicity (kg 1,4-DCB)	-1.6E-02	1.9E-02	-2.7E-02	-8.5E-03
Freshwater ecotoxicity (kg 1,4-DCB)	-1.3E-02	1.4E-02	-2.2E-02	-7.1E-03
Terrestrial acidification (kg SO_2 eq)	-1.0E-03	1.3E-03	-3.3E-03	1.1E-03
Mineral resource scarcity (kg Cu eq)	-9.3E-04	1.6E-04	-1.2E-03	-6.8E-04
Ozone formation, Terrestrial ecosystems (kg NOx eq)	-5.4E-04	1.1E-04	-6.9E-04	-3.5E-04
Ozone formation, Human health (kg NOx eq)	-5.3E-04	1.1E-04	-6.8E-04	-3.5E-04
Fine particulate matter formation (kg PM2.5 eq)	-3.5E-04	1.7E-04	-6.3E-04	-5.9E-05
Marine eutrophication (kg N eq)	-2.2E-04	3.2E-04	-7.7E-04	2.5E-04
Freshwater eutrophication (kg P eq)	-7.1E-05	7.6E-05	-1.6E-04	3.3E-07
Stratospheric ozone depletion (kg CFC11 eq)	-1.6E-06	1.7E-06	-4.3E-06	1.4E-06

* The reported mean is the average difference of 2020-2010, thus, negative values indicate that 2020 production had lower impact.

Table 14. Agri-Stats lifecycle inventory.

Operation	Benchmarking item	2010	2020
Broilers	U.S. Broilers	8,447,107,031	9,229,819,998
Broilers	Average live wt.	5.74	6.37
Broilers	Total live lbs. produced	48,486,394,357	58,793,953,386
Broilers	Actual FCR	1.96	1.79
Broilers	Breeders		
Broilers	Day old chicks placed	70,552,105	79,561,646
Broilers	% Mortality in grow	5.22%	7.15%
Broilers	Tons of feed consumed	1,037,116	1,151,655
Broilers	% Corn	59%	59%
Broilers	% SBOM	25%	25%
Hens	Hens housed	66,869,285	72,018,617
Hens	Dozen hatching eggs produced	869,300,711	949,445,428
Hens	Lbs. feed per doz. hatching eggs	6.88	6.71
Hens	Tons of feed consumed	2,990,394	3,185,389
Hens	% Corn	61%	61%
Hens	% SBOM	25%	25%
Hatchery	Number of chicks hatched	8,800,903,345	9,716,622,800
Hatchery	BTUs electricity per chick	191	205
Hatchery	BTUs gas/oil per chick	169	163
Hatchery	Dozen hatching eggs transported	869,300,711	949,445,428
Hatchery	Chicks delivered	8,800,903,345	9,716,622,800
Hatchery	Dozens of eggs/trip	7,904	8,990
Hatchery	Average miles per trip	82	95
Hatchery	Average number of chicks/trip	70,905	78,798
Hatchery	Average miles per trip	77	88
Feed Milling	Tons of feed produced	47,516,666	52,620,588
Feed Milling	BTUs electricity per ton	52,066	52,785
Feed Milling	BTUs gas per ton	146,241	146,766
Feed Milling	Tons delivered	47,516,666	52,620,588
Feed Milling	Average tons per trip	24.60	24.80
Feed Milling	Average miles per trip	64	65
Broiler grow out	Total live lbs. produced	48,486,394,357	58,793,953,386
Broiler grow out	Total tons of feed consumed	47,516,666	52,620,588
Broiler grow out	Tons of starter feed	5,702,000	6,051,368
Broiler grow out	Tons of corn used	3,177,725	3,552,153
Broiler grow out	Tons of soybean meal used	1,635,904	1,886,816
Broiler grow out	Tons of DDGS	244,046	142,207
Broiler grow out	Supplemental lysine	8,211	11,074
Broiler grow out	Tons of supplemental TSAA	14,597	19,485
Broiler grow out	Tons of grower feed	14,920,233	15,259,971
Broiler grow out	Tons of corn	8,705,956	9,487,124

Table 14. Agri-Stats lifecycle inventory.

Operation	Benchmarking item	2010	2020
Broiler grow out	Tons of soybean meal	3,531,619	3,981,326
Broiler grow out	Tons of DDGS	838,517	386,077
Broiler grow out	Tons of supplemental lysine	23,574	27,468
Broiler grow out	Tons of supplemental TSAA		43,338
Broiler grow out	Tons of WD1 feed	10,168,567	11,734,391
Broiler grow out	Tons of corn	6,223,163	7,694,240
Broiler grow out	Tons of soybean meal	2,145,568	2,829,162
Broiler grow out	Tons of DDGS	626,384	289,839
Broiler grow out	Tons of supplemental lysine	156,596	19,948
Broiler grow out	Tons of supplemental TSAA	198,287	30,275
Broiler grow out	Tons of WD2 feed	16,725,867	19,574,859
Broiler grow out	Tons of corn	10,751,387	13,252,179
Broiler grow out	Tons of soybean meal	2,940,407	4,226,212
Broiler grow out	Tons of DDGS	1,125,651	479,584
Broiler grow out	Tons of supplemental lysine	24,922	31,516
Broiler grow out	Tons of supplemental TSAA	28,099	44,631