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## Life-cycle analysis of soybean meal, distiller-dried grains with solubles, and synthetic amino acid-based animal feeds for swine and poultry production

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## ABSTRACT

Swine and poultry meat production are two important sectors in the U.S. economy. They play an important role in environmental sustainability because they contribute to the greenhouse gas (GHG) emissions as the result of agricultural and production activities. To improve the sustainability of swine and poultry meat production, it is important to understand the environmental effects and identify the key drivers of the production activities. In this work, we presented an environmental assessment of the production of swine (i.e., pork) and poultry (i.e., broiler chicken). We conducted a life-cycle analysis of formulating animal feeds using soybean meal, corn, distiller-dried grains with solubles (DDGS), and synthetic amino acids as candidate ingredients to produce swine and poultry. We evaluated GHG emissions, fossil fuel consumption, and water consumption from formulating and utilizing a variety of animal feeds based on these ingredients for swine and poultry production, using an expanded version of the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET<sup>®</sup>) model. With pork and broiler chicken as the finished products, the functional unit was defined as one kg of live-weight animal at the farm gate. Feed production was the major contributor to the life-cycle GHG emissions (88 % and 91 % of the total GHG emissions for swine and poultry production, respectively) and fossil fuel consumption (79 % and 84 % of the total fossil fuel consumption for swine and poultry process, respectively). Among the four ingredient types, amino acids had the biggest GHG emission footprint; however, DDGS had the largest effect on increasing GHG emissions of swine and poultry production.

**Abbreviations:** ANL, Argonne National Laboratory; AA, amino acid; CO<sub>2</sub>e, carbon dioxide equivalent; CP, crude protein; CH<sub>4</sub>, methane; DDGS, distiller-dried grains with solubles; FAO, Food and Agriculture Organization of the United Nations; FFC, fossil fuel consumption; GHG, greenhouse gas; GREET, Greenhouse gases, Regulated Emissions, and Energy use in Transportation; g, gram; HCL, hydrochloride; H<sub>2</sub>S, hydrogen sulfide; HCN, hydrogen cyanide; Kg, kilogram; LCA, life-cycle analysis; LW, live weight; LCI, life-cycle inventory; l, liter; LPG, liquid propane gas; Mt, metric ton; M&B, meat and bone meal; MJ, megajoule; N<sub>2</sub>O, nitrous oxide; PPEFC, Pig Production Environmental Footprint Calculator; U.S., United States; USDA, United States Department of Agriculture; WDGS, wet distiller grain solubles; WC, water consumption

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## 1. Introduction

Food demand will rise as the population grows. In 2015, when the world population was approximately 7.2 billion, about 41 kg of meat (including pork, beef, poultry, and lamb) was consumed per capita worldwide. By 2030, when the population is projected to be at 9.3 billion, 52 kg of meat per capita is expected to be consumed (Statista, 2019) (United Nations, 2015). The U.S. food industry, from farm to consumer, plays an important role in the U.S. economy; however, this economic sector is facing pressure to address environmental concerns as well. While food demand and adequate supplies benefit public health, food production plays an important role in environmental sustainability since it contributes to the increase of greenhouse gas (GHG) emissions. For example, total emissions from global livestock are about 7.1 gigatonnes of equivalent carbon dioxide (CO<sub>2</sub>e) per year, which represents about 15 % of all anthropogenic GHG emissions (FAO, 2019). Development of more sustainable diets for animals has become a top priority in the food production industry (Griep and Binder, 2017); therefore, to improve sustainability in the meat production process, it is important to understand what the key drivers of this supply chain are regarding its sustainability. For instance, Binder (2017) argued that one alternative to improving sustainability performance in livestock production is using crude protein-reduced diets by supplementing essential amino acids. In this paper, we focused our analysis on two major U.S. meat industries—swine and poultry production—by closely examining the main animal feed ingredients used in these industries. Currently, pork is the most widely consumed meat in the world, while poultry is the fastest growing meat industry (World Watch Institute, 2019). The U.S. is the world's largest producer and the second largest exporter of poultry meat (USDA, 2019a), while it is the world's third largest producer and consumer of pork and pork products (USDA, 2019b). Soybean meal and distiller-dried grains with solubles (DDGS) from corn ethanol plants are two major animal feed ingredients used in these industries. The U.S. production of DDGS has quadrupled since 2005 as U.S. corn ethanol has increased dramatically during the same period, accounting for more than 40 million metric tons (Mt) (Beckman and Nigatu, 2017). U.S. soybean meal production has increased from 22 million Mt in 1984 to an estimated 42 million Mt produced in 2017 (USDA, 2019c), placing the U.S. as the world's second largest producer of this product, after China (Soybean Meal Info Center, 2018). Further, synthetic amino acids (AAs) such as L-lysine hydrochloride (HCL), threonine, and DL-methionine are also used extensively as animal feed additives and are produced from different bio-based sources such as sugarcane, soybeans, corn, or natural protein resources (keratin, soybean) (Scheper et al., 2003).

The different stages that are involved in swine and poultry production—from crop farms, feed processing, animal farms, meat processing, and finally to human consumption—require energy and material inputs that contribute to environmental impacts, such as GHG emissions and water consumption, of the meat supply chain. Life-cycle analysis (LCA) takes a holistic approach to evaluating the environmental impacts of each stage of swine and poultry production, identifying the key drivers that influence GHG emissions and other sustainability metrics, and helping pursue opportunities to mitigate the adverse environmental impacts.

Previous researchers have conducted LCAs of swine and poultry production. For instance, Reckmann et al. (2013) and Reckmann et al. (2016) provided data for an environmental profile of pork production in Germany, while Sandefur et al. (2015) described the development of life-cycle inventory datasets for swine production practices in the U.S. Furthermore, Gonzales-Garcia et al. (2014) performed an environmental assessment of broiler chicken production in Portugal, and Putman et al. (2017) evaluated the LCA changes in the U.S. poultry industry from 1965 to 2010. Skunca et al. (2015) also presented a review of several LCAs of poultry industries from different countries including the U.S., Brazil, and European countries. These studies concluded that feed production and on-farm emissions were the main contributors to the GHGs of meat supply chains. However, very few of the studies explored the sustainability implications of the different ingredients used to formulate animal diets.

In this paper, we evaluated GHG emissions that included carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) calculated on the basis of the 100-year global warming potential of the production and use of soybean meal, corn, DDGS, and AAs (L-lysine HCL, threonine, and DL-methionine) as key ingredients for formulating animal feeds for swine and poultry production. We also evaluated fossil fuel consumption (FFC) and water consumption (WC) metrics. We assessed the energy and environmental effects of using a variety of animal feed diets based on the key animal feed ingredients for swine and poultry production. For this analysis, we used an expanded Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model (ANL, 2018). The GREET model was developed to evaluate the energy and environmental impacts of advanced biofuels and their co-products including soybean meal and DDGS and bio-derived chemicals.

## 2. Materials and methods

In this work, an LCA from the field to animal farm gate was performed to assess the energy and environmental footprints of production for poultry and swine with diets formulated from soybean meal, DDGS, corn, and AAs. The system boundary is presented in Fig. 1 the data used for this model was collected from literature or provided by animal feed experts. With pork and broiler chicken as the finished products, the functional unit is defined as one kg of live-weight (LW) animal at the animal farm gate. The system boundary covers all material and energy flows associated with production of animal feed ingredients (including crop cultivation and processing and chemical production such as AAs), formulation of diets, and animal farming, as detailed below. For this analysis, we expanded the GREET model to conduct an LCA of formulating animal feeds for swine and poultry production.

Fig. 1. System boundary for life-cycle analysis of the production of swine and poultry.

### 2.1. Crop and ingredients production

Although a great variety of diets for poultry and swine production exist, the main ingredients utilized are typically similar. For

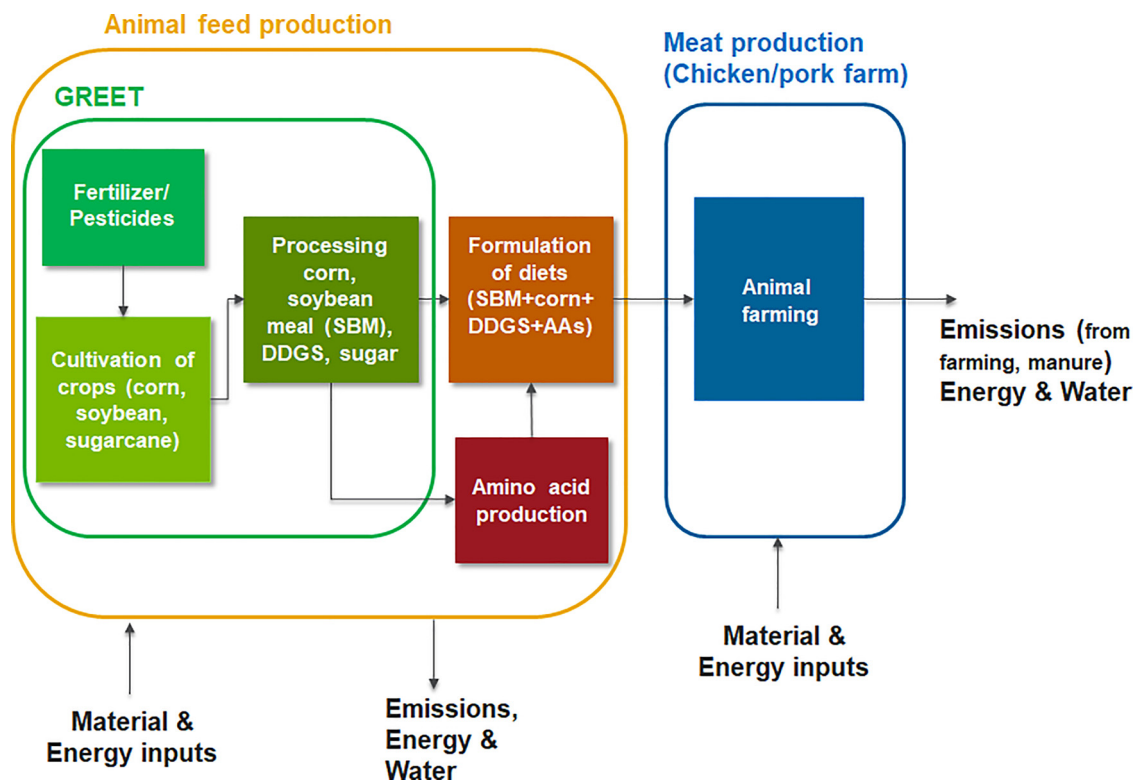


Fig. 1. System boundary for life-cycle analysis of the production of swine and poultry.

this analysis, we focused on the following ingredients: corn, soybean meal, DDGS, and synthetic AAs. DDGS are co-produced along with corn-based ethanol in ethanol plants, while soybean meal results from the extraction of soybean oil from soybeans. It is critical to quantify the energy and material requirements it takes to produce such ingredients so that the environmental impacts associated with the production of these ingredients are appropriately captured. For corn, the farming energy, water, fertilizer, and herbicide inputs that are required were taken into account to quantify its energy use, GHG emissions, and water consumption (details can be found in the Supplementary Information [SI]). The processes involved in DDGS production also co-produced corn ethanol, as shown in Fig. S1 in the SI, so we carefully investigated which processes were responsible for DDGS production or ethanol production, or both, and determined how much of the process energy and material requirements should be allocated to each product. When a particular process was entirely responsible for producing one particular product, the entire energy and material inputs were attributed to the product. For example, reducing the moisture content of wet distiller grain solubles (WDGS) to meet the target of DDGS through drying is a dedicated step for producing DDGS. Therefore, the energy use, associated emissions, and water consumption impacts for drying WDGS were entirely attributed to DDGS production. On the other hand, the energy-intensive distillation step to produce anhydrous ethanol after corn starch fermentation is solely related to ethanol production. Therefore, ethanol production is fully responsible for the distillation energy requirement and none of this energy requirement was attributed to DDGS production. Because producing DDGS and ethanol takes corn as the feedstock and goes through a fermentation process involving the use of process energy and chemicals, the energy, emissions, and water consumption associated with corn farming and transportation to the ethanol plant, as well as the subsequent fermentation process, needs to be allocated between DDGS and ethanol. For this analysis, we allocated the energy, emission, and water consumption based on the relative ratio of DDGS and ethanol. The so-called mass-based and market value-based allocation methods were used in this analysis when the relative ratio was calculated based on their mass outputs and market values, respectively. With the mass-based allocation method, it was assumed that to convert the feedstock into the different products, the same amount material and energy inputs were required to produce the same number of products by mass. The market value-based method allocates the GHG emissions and energy consumption burdens assuming that the greater market value of individual products requires greater amounts of energy and material inputs (Wang et al., 2015). For soybean meal, we took the same approach and allocated the energy, emission, and water consumption associated with soybean farming, transportation to the oil extraction facility, and the soy oil extraction resulting in soybean meal, using the mass- and market value-based allocation methods. Details of the allocation methods used in this work can be found in SI Section S1. We used data from the corn ethanol and soybean biodiesel production pathways available in GREET to quantify and allocate, as described earlier, the energy, emission, and water consumption impacts of producing DDGS and soybean meal as animal feed ingredients (Arora et al., 2008; Huo et al., 2009; Han et al., 2014; Wang et al., 2015; Han et al., 2017; Chen et al., 2018).

For synthetic AAs, we relied on published information related to production of different AAs. In particular, we found life-cycle

**Table 1**

Material and energy inputs to produce one kg of amino acids: L-lysine, threonine, and DL-methionine (Mosnier et al., 2011).

Material Input (g/kg of AA <sup>b</sup> )	L-Lysine HCL	Threonine	DL-Methionine
Sugar	100	100	n/a <sup>a</sup>
Maize starch	500	500	n/a <sup>a</sup>
Wheat starch	500	500	n/a <sup>a</sup>
Liquid ammonia	300	300	n/a <sup>a</sup>
Propylene	n/a <sup>a</sup>	n/a	430
Hydrogen sulfide (H <sub>2</sub> S)	n/a <sup>a</sup>	n/a <sup>a</sup>	270
Methanol	n/a <sup>a</sup>	n/a <sup>a</sup>	390
Hydrogen cyanide (HCN)	n/a <sup>a</sup>	n/a <sup>a</sup>	210
Energy Input (MJ/kg of AA <sup>b</sup> )			
Electricity	17.91	17.91	3.72
Natural gas	17.91	17.91	3.72

<sup>a</sup> n/a, not applicable.<sup>b</sup> AA, amino acid.

inventories (LCIs) for the most commonly used synthetic AAs in animal feed production: L-lysine HCL, threonine, and DL-methionine. The LCI data are shown in Table 1. Some of the material requirements for production of these compounds were readily available in the GREET model, except sugar, wheat, and hydrogen cyanide. Therefore, new inventories were added to the GREET model. Details related to sugar, wheat, and hydrogen cyanide production can be found in the SI Section S2. Besides, we treated hydrogen sulfide as a burden-free byproduct from the petroleum refining sector (Elgowainy et al., 2014).

Table 1. Material and energy inputs to produce one kg of amino acids: L-lysine, threonine, and DL-methionine (Mosnier et al., 2011)

## 2.2. Animal diet formulations and feed preparation

A variety of factors influenced the use of ingredients in the formulation of animal feeds. Not only was the cost of delivering specific nutrients a consideration in the use of an ingredient, but other physical and market factors as well. Table 2 presents different composite diets for swine and poultry containing only the key ingredients studied in this analysis (soybean meal, corn, DDGS, and synthetic AAs). During the life-cycle of a growing animal, different diets are used as the animal ages. Diets for young animals tend to be more nutrient-dense than those fed to older animals and are consumed at a lower rate. The composite diet was intended to

**Table 2**

Composite diets (g/kg) used for the entire production cycle associated with broiler and pork production.

	Standard Diet: Corn-soy	Diet A: Corn-soy with 84 g/kg DDGS <sup>c</sup>	Diet B: Corn-soy with 126 g/kg DDGS <sup>c</sup>	Diet C: Corn-soy with M&B <sup>a</sup>	
<b>Poultry diets (g/kg)<sup>b</sup></b>					
Soybean meal	273.5	255.7	247.6	246.4	
Corn	721.4	655.5	621.4	748.3	
DDGS <sup>c</sup> as 29% CP <sup>d</sup> and 7 % Fat	0.0	83.8	126.2	0.0	
DL-methionine	2.4	2.2	2.0	2.5	
Threonine	0.9	0.7	0.5	0.9	
L-lysine HCL	1.8	2.1	2.2	1.9	
<b>Swine diets (g/kg)<sup>e</sup></b>					
	Standard Diet: Corn-soy	Diet A: Corn-soy with 105 g/kg DDGS <sup>c</sup>	Diet B: Corn-soy with 211 g/kg DDGS <sup>c</sup>	Diet C: Corn-soy with 318 g/kg DDGS <sup>c</sup>	Diet D: Corn-soy with M&B <sup>a</sup>
Soybean meal	124.1	73.9	23.1	0.0	77.4
Corn	870.0	814.4	758.1	673.7	915.9
DDGS <sup>c</sup> as 29% CP <sup>d</sup> and 7 % Fat	0.0	104.9	211.0	318.7	0.0
DL-Methionine	0.6	0.4	0.2	0.0	0.8
Threonine	1.1	1.3	1.4	1.2	1.3
L-Lysine HCL	4.1	5.2	6.2	6.4	4.6

Note: all ingredients are shown on a 100 % dry basis.

<sup>a</sup> M & B, meat and bone meal, which is a source of animal protein and other nutrients such as calcium and phosphorus.

<sup>b</sup> Other ingredients are animal fat, M&B, monocalcium phosphate, limestone, and salt. However, these additional ingredients are not included in the analysis. See SI Section S3 Table S3a.

<sup>c</sup> DDGS, distiller-dried grains with solubles.

<sup>d</sup> CP, crude protein.

<sup>e</sup> Other ingredients are animal fat, M&B, monocalcium phosphate, limestone, salt, and L-tryptophan. However, these additional ingredients are not included in the analysis. See SI Section S3 Table S3b.

represent the total amount of each ingredient consumed across all production stages for swine or poultry. The complete list of ingredients and their compositions for all diets are described in detail in the SI (see Section S3 of the SI). Over the years, diet specifications have changed to correspond to animal genetic improvements. While nutrient requirements are fairly standard for a given genetic background and type of production, there are still differences in how diets are formulated based on ingredient availabilities and costs. The genetic background, market weight, sex, and market age are some of the factors involved in diet formulation (Leeson and Summers, 2008). For example, the diets presented here for broiler chicken were intended to reflect the feed consumed to produce a 3.2 kg (7 lb), 52 day-old broiler with a feed conversion ratio of 1.85 kg of feed per kg of animal body weight gain. For the case of swine, the estimates were for a 125.6 kg (277 lb) hog with a feed conversion ratio of 2.54 kg feed per kg of animal body weight gain. Ingredient availability and pricing were additional considerations. Since all the diets for a given type of animal production were formulated to be nutritionally similar, we were assuming the same performance in terms of rate of growth, feed efficiency, and days on feed to produce swine or poultry. Production and use of vitamins, trace minerals, and other pharmaceutical components were assumed similar within a given type of animal diet and were not included in this analysis. For the purpose of this analysis, the information provided here deals only with growing animals, which consume the vast majority of feed, and does not include the feed used by breeding stock. The composite diets presented in Table 2 were intended to illustrate how diet formulations can differ based on different ingredient availability and cost scenarios. Although this work did not focus on the cost of animal feeds, it is known that diet costs are often reduced with the incorporation of DDGS due to it being priced to encourage its usage. Therefore, the DDGS content was increased in each diet while soybean meal and corn contents were reduced. As a point of reference, we used standard diets for both animals with typical composition ratios (g/kg) of corn, soybean meal, DDGS, and AAs. For the poultry case, diets A and B slightly reduced the soybean meal, corn, and two of the AAs (DL-methionine and threonine) while increasing DDGS and L-lysine HCL content. For swine diets, the trend of diet composition was similar to that of the poultry diets. The last diet (diet C for poultry and diet D for swine) replaced the DDGS content to increase meat and bone meal (M&B) (using more corn and less soybean meal). All these variations followed the nutrient profiles to fulfill animal nutrition requirements.

Table 2. Composite diets (g/kg) used for the entire production cycle associated with broiler and pork production

All these ingredients were combined and processed to obtain the appropriate formulation for the animals to consume. During this process, energy was used to mix these ingredients. The estimated values for energy and water inputs for both swine and poultry food diet preparation are shown in Table 3.

Table 3. Summary of energy inputs for animal feed preparation

### 2.3. Live animal production

Data related to on-farm animal growth for both swine and poultry is presented in Table 4. This table shows the energy consumption, such as electricity, consumed for lighting, ventilation, feeding as well as heat, and natural gas and water use for farming activities. These data, however, were presented in an aggregated form for the different animal growing stages (i.e., starter, growing, and finishing). For the case of the swine production, the Pig Production Environmental Footprint Calculator (PPEFC) was used to obtain live production parameters. The PPEFC used mathematical relationships to model swine production systems from growing, feeding intake, on-farm energy and water consumption, and manure handling. It was created by the University of Arkansas Center for Agricultural and Rural Sustainability for the National Pork Board (Sandefur et al., 2015; National Pork Board, 2019). Inventory data for on-farm poultry production was obtained from Putman et al. (2017). We assumed 1000 market LW broiler with an average feed conversion ratio of 1.85 kg of feed per kg of broiler chicken for the entire production cycle. Similarly, for pork we assumed 1000 market LW hogs with an average feed rate consumption of 2.54 kg of feed per kg of pork for the entire production cycle.

Table 4. Inventory data of swine and poultry production at the animal farm

### 2.4. Manure management

Manure is an important source of emissions (mainly CH<sub>4</sub> and N<sub>2</sub>O) as well as a source of nutrients such as nitrogen, phosphorous, potassium, etc., for crops. There are other solid waste involved in animal farming such as poultry beds that are usually composed of a mixture of sawdust or wood chips. However, we did not include the emissions and energy burdens for production or handling of these materials due to a lack of information. The quantity of manure produced, manure characteristics, manure management systems, and climate are the key factors that affect CH<sub>4</sub> production from different livestock manure (Jun et al., 2001). For this analysis, we used

**Table 3**  
Summary of energy inputs for animal feed preparation.

Input (MJ/kg of animal feed)	Swine <sup>a</sup>	Poultry <sup>b</sup>
Electricity	14,049	137,001
Residual oil	57,592	n/a <sup>c</sup>
Natural gas	n/a <sup>c</sup>	52,940
Water (l/kg of animal feed)	0.02	0

<sup>a</sup> Data obtained from Reckmann et al. (2016).

<sup>b</sup> Data obtained from Pelletier (2008).

<sup>c</sup> n/a, not applicable.

**Table 4**  
Inventory data of swine and poultry production at the animal farm.

Process Parameters per 1000 Animals Produced	Swine	Poultry
Average LW <sup>a</sup> animal at farm gate (kg)	125.6	3.2
Total feed (dry kg/yr)	319,111	5874
Total feed (dry kg/kg animal live-weight gain)	2.5	1.9
Energy Input (MJ/kg LW <sup>a</sup> Animal at Farm Gate)	Swine <sup>b</sup>	Poultry <sup>c</sup>
Electricity	523,629	312,614
Natural gas	711,151	n/a <sup>d</sup>
Diesel	55,615	69,036
Gasoline	13,258	n/a <sup>d</sup>
LPG (liquid propane gas)	n/a <sup>d</sup>	283,097
Water (l/kg LW <sup>a</sup> animal at farm gate)	29.5 <sup>e</sup>	3.8 <sup>e</sup>

<sup>a</sup> LW, live weight.

<sup>b</sup> Energy input data obtained from [National Pork Board \(2019\)](#).

<sup>c</sup> Energy input data obtained from [Putman et al. \(2017\)](#).

<sup>d</sup> n/a, no applicable.

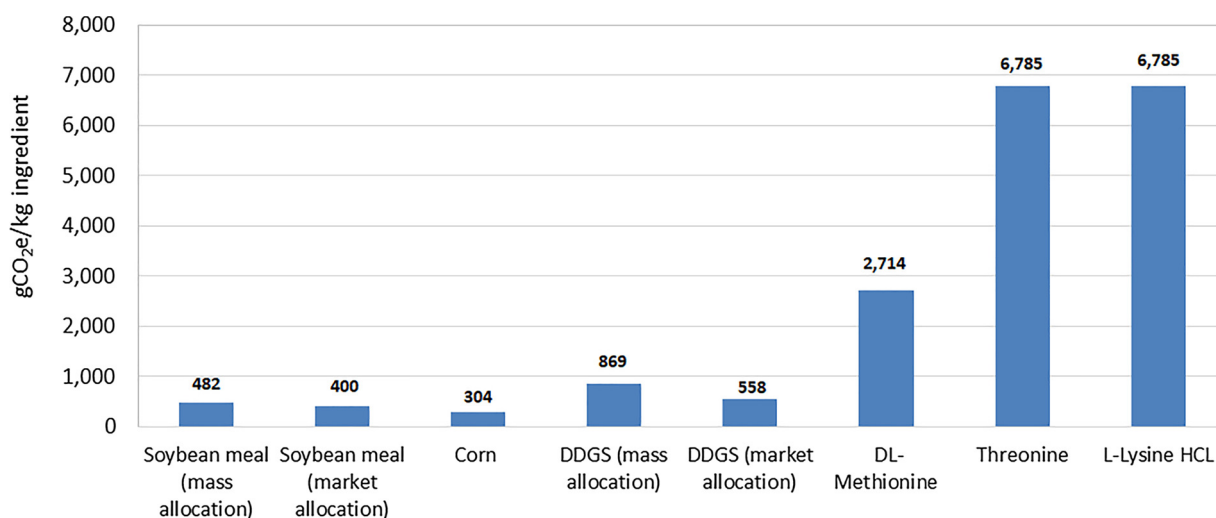
<sup>e</sup> This water represents total water used during farming activities including process water for cleaning and cooling and intake water for animal consumption.

manure handling methods for the U.S. reference cases presented in Table S4b in the SI for both swine and poultry manure. More details regarding the manure management system and key parameters for manure emission calculations are found in the SI.

We calculated the direct CH<sub>4</sub> and N<sub>2</sub>O emissions to the atmosphere that resulted from chicken and pork manure handling and the potential application to soil as fertilizer (details are presented in the SI). The application of the manure as an organic fertilizer avoided the use of conventional nitrogen-based fertilizer, which was included in the analysis as credits to on-farm GHG emissions. Manure production varies by animal type and the type of farm and is relative to the weight of the animal and feed intake ([Jun et al., 2001](#)). The manure production for broiler operations was obtained from [Leeson and Summers \(2008\)](#). According to these authors, the manure from broiler operation was correlated to the amount of feed consumed per animal, that is, 0.27 kg of manure per kg of feed consumed is equivalent to 0.5 kg of manure per kg LW animal at the farm gate. In the case of swine manure production, we obtained information from the PPEFC model ([Sandefur et al., 2015](#); [National Pork Board, 2019](#)) where 0.38 kg of manure per kg LW animal at the farm gate was estimated. However, due to a lack of information on manure production among different diets for both animal operations, we assumed a constant value for manure production among all diets.

### 3. Results

**Fig. 2** presents the carbon intensity (gCO<sub>2</sub>e/kg) of what it took to produce one kg of each of the main ingredients used in swine and poultry diets. The AAs (i.e., DL-methionine, threonine, and L-lysine HCL) had the highest GHG emissions because of their high energy-intensive production process and material inputs. These results were consistent and followed the same trends with values reported in the literature ([Reckmann et al., 2016](#); [Mosnier et al., 2011](#)). As we mentioned before, DDGS and soybean meal are co-produced along with other important products such as corn-based ethanol and soybean oil; therefore, we needed to evaluate different



**Fig. 2.** Carbon intensity using mass and market allocations for main ingredients in swine and poultry diets.

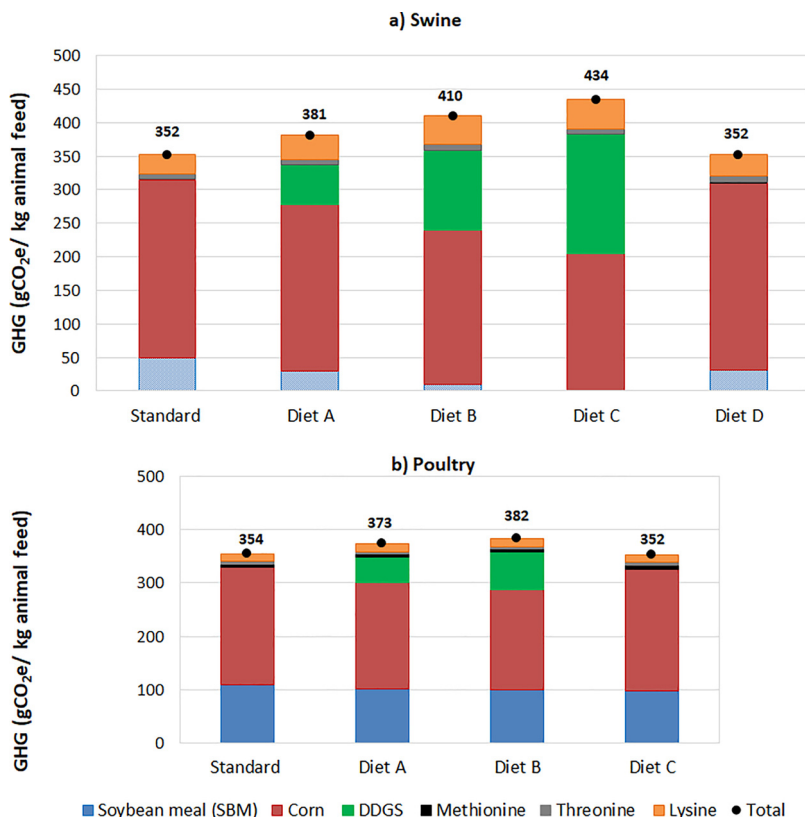


Fig. 3. Greenhouse gas emission contribution of each ingredient per one kg of animal feed for a) swine and b) poultry diets. Note: both subfigures a) and b) are calculated based on market allocation method.

allocation methods to distribute the emission burdens between co-products. Fig. 2 compares two carbon intensities for DDGS and soybean meal when mass allocation and market value-based methods are used to allocate the emission burdens based on their mass output shares or market values (see SI for details). Production of DDGS was more GHG-intensive than producing soybean meal and corn because DDGS production involves more processing steps such as corn oil extraction and drying WDGS. This latter step was energy-intensive and contributed to 32 % (mass allocation case) and 50 % (market allocation case) of the total GHG emissions to produce one kg of DDGS (see SI Section S1). For both ingredients, if the market value method was used instead of mass allocation, then the carbon intensity was reduced. For instance, DDGS carbon intensity was reduced 36 % from 869 to 558 gCO<sub>2</sub>e per kg of DDGS produced due to the lower market price of DDGS at \$0.15/kg (equivalent to \$0.10/l of ethanol produced) compared to ethanol's price of \$0.37/l (U.S. Bioenergy Statistics, 2019). Similarly, the carbon intensity of soybean meal was reduced from 482 to 400 gCO<sub>2</sub>e per kg due to the lower market price of soybean meal (\$0.37/kg, USDA, 2019d) compared to soybean oil (\$0.73/kg, U.S. Bioenergy Statistics, 2019). Economic factors played an important role in deciding the type of ingredient and its share in the diet. As we mentioned before, the incorporation of DDGS reduced the cost of diets. Therefore, the following results are presented using market allocation to align with the decision criteria for diet formulation. The results using the mass allocation method can be found in the SI Section S5.

Fig. 2. Carbon intensity using mass and market allocations for main ingredients in swine and poultry diets.

Fig. 3 represents the contribution to the GHG emissions of each ingredient used to produce one kg of animal feed for swine and poultry diets. The diet with the highest GHG value in terms of gCO<sub>2</sub>/kg of animal feed corresponded to the diet with the largest DDGS content. Fig. 4, on the other hand, presents the field-to-farm gate GHG emission results for swine and poultry production using a variety of swine and poultry diets. As expected, the emissions from swine production were higher than those from poultry production due to the higher feed intake (dry matter) per kg of LW for swine than for poultry.

Fig. 3. Greenhouse gas emission contributions of each ingredient per one kg of animal feed for a) swine and b) poultry diets. Note: both subfigures a) and b) are calculated based on market allocation method.

Fig. 4. Field-to-farm-gate greenhouse gas emissions of animal growth using different diets for a) swine and b) poultry production. Note: both subfigures a) and b) are calculated based on market allocation method.

Fig. 4 also shows the GHG emissions breakdown between animal feed production and animal farming. Emissions during animal feed production contributed to the majority of the estimated field-to-farm-gate impacts associated with production of both animal types. The remaining contribution was attributed to the energy and material inputs required during animal farming, in addition to CH<sub>4</sub> and N<sub>2</sub>O emissions that resulted from manure of the animals. However, the impact of these latter emissions was very small

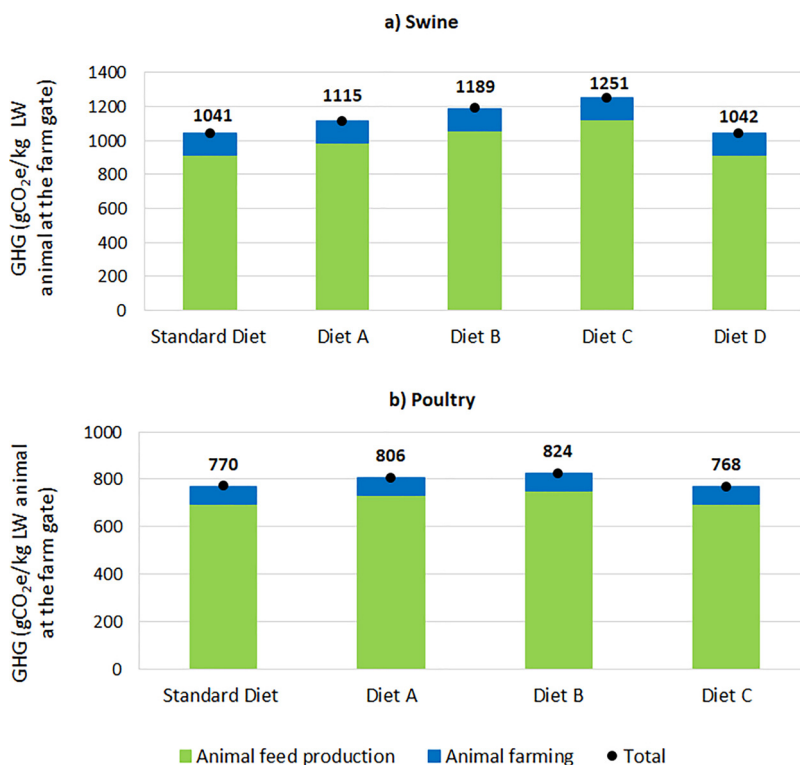


Fig. 4. Field-to-farm-gate greenhouse gas emissions of animal growth using different diets for a) swine and b) poultry production. Note: both subfigures a) and b) are calculated based on market allocation method.

compared to those emissions that resulted from the energy used for lighting, ventilation, feeding, and heating operations. For instance, swine manure emissions were 0.2 gCO<sub>2</sub>e/kg LW compared to 129 gCO<sub>2</sub>e/kg LW during pork farming operation, while poultry manure emissions corresponded to 0.1 gCO<sub>2</sub>e/kg LW compared to 74 gCO<sub>2</sub>e/kg LW during chicken farm operations. The high moisture content of manure and the method for handling and controlling manure emissions were key aspects that contributed to these emissions (see SI Section S4). As shown in Fig. 4a, the GHG emissions with diets A, B, and C increased by 7%, 14%, and 20%, respectively, when compared to the GHG emissions of the standard diet. Diet D, on the other hand, provided 0.1% less GHG emissions compared to those using standard diet. Both the standard diet and diet D did not contain any DDGS, but the corn composition slightly increased from 87% to 92% while the soybean meal composition decreased from 12% to 8%. For the case of poultry production (Fig. 4b), the results followed a similar trend. However, the differences in the GHG emissions were only 5%, 7%, and -0.3% for diets A, B, and C, respectively, when they were compared to the standard diet. In this case, the increase of DDGS and decrease of corn and soybean meal were very small, as shown in Table 2. Any GHG emission credits due to manure application as nitrogen fertilizers were also included in the GHG emissions during the animal farming activities. However, due to the small nutrient composition in both swine and poultry manure, the credits were very small and had an insignificant effect on the overall GHG results.

Other sustainability metrics measured in this analysis were the FFC and WC, whose results are presented in Fig. 5 for swine and poultry production using different diets. As expected, the FFC followed trends that were similar to those of GHG emissions; in other words, increased FFC resulted from the increased share of DDGS in diets, while the increased share of corn and soybean meal resulted in decreased FFC. For the case of swine production, FFC was increased by 16%, 32%, and 50% with diets A, B, and C, respectively, when compared to the standard diet, while for poultry production, the FFC was increased by 13% and 20% for diet A and B, respectively, when compared to the poultry standard diet. Fossil fuel consumption for diet D in the swine case and diet C in poultry case were similar to the standard diet as these diets (D, C and standard) do not have DDGS, which is the major driver of the results. Water consumption also differed with the variation of ingredients in the diets. For instance, WC of swine production decreased 6%, 13%, 17%, and 4% for the case when diets A, B, C, and D were used, respectively, compared to the standard diet case. These results were driven by the reduction of soybean meal and corn composition in these diets. These two ingredients are known to be from water-intensive crops due to irrigation activities (Lampert et al., 2015).

Fig. S6 in the SI presents the water intensities (l/kg) for the main ingredients of swine and poultry diets included in this work. In the case of poultry production, the differences in WC among the different diets were minor (-3%, -5%, and -2% for diets A, B, and C, respectively) due to the small variation of soybean meal and corn composition in the poultry diets and the fact that poultry were efficient in using diets.

Fig. 5. Field-to-farm-gate fossil fuel consumption and water consumption of animal growth for a) swine and b) poultry production.

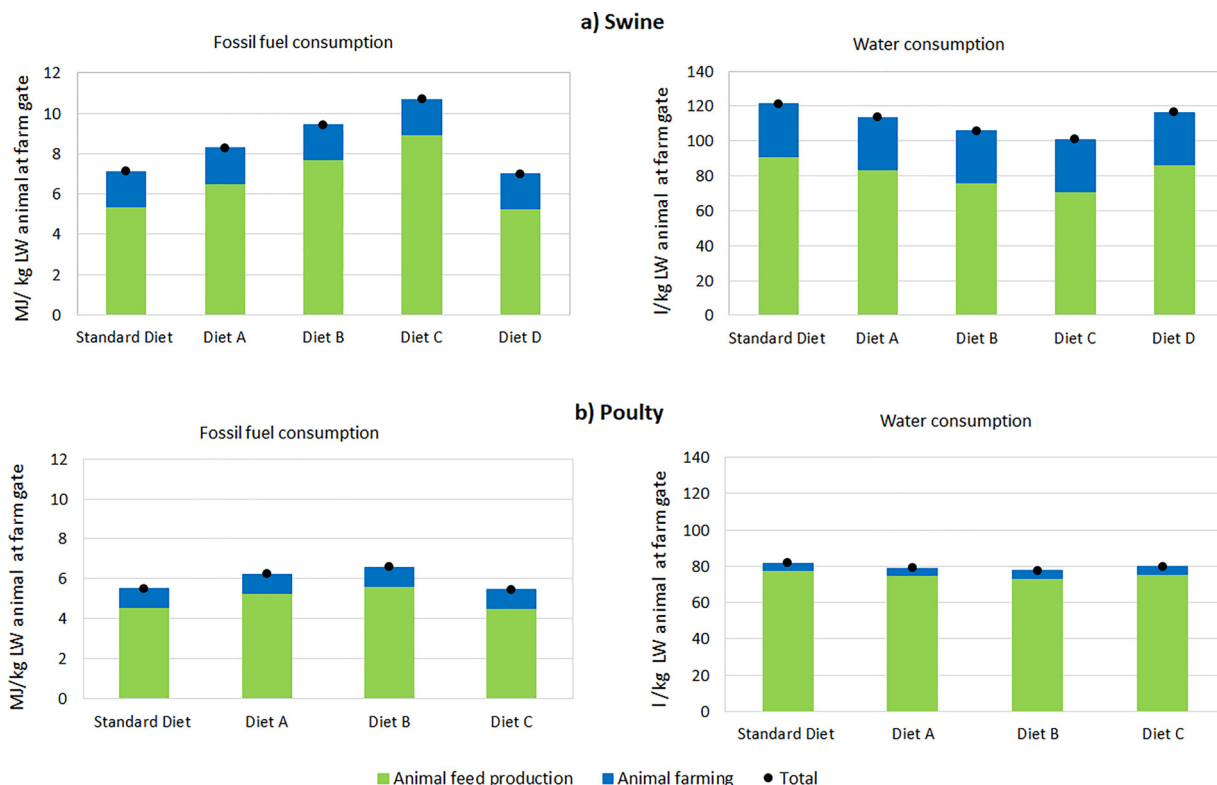


Fig. 5. Field-to-farm-gate fossil fuel consumption and water consumption of animal growth for a) swine and b) poultry production. Note: both subfigures a) and b) are calculated based on market allocation method.

### 3.1. Sensitivity analysis: Market vs. Mass allocation for DDGS

The results presented previously were obtained using market value to allocate the energy, emission, and water consumption impacts of producing DDGS and soybean meal as animal feed ingredients. However, we also explored the mass-based allocation method. Details of the allocation method calculations are shown in the SI Section S1, and figures for the GHG emission contribution of each ingredient per kg of animal feed, field-to-farm-gate GHG emissions, FFC, and WC of animal growth using different diets when the mass allocation method was used can be found in SI Section S5.

Fig. 6 compares GHG emissions of animal growth under the different diets between the market and mass allocation methods. For swine production, GHG emissions for standard, A, B, C, and D diets increased by 2 %, 9 %, 14 %, 20 %, and 2 %, respectively, when the allocation method was switched from market value to mass. Similarly, for poultry diets, the GHG emissions for standard, A, B, and C diets increased by 7 %, 11 %, 13 %, and 5 %, respectively, compared to the base case scenario (market value allocation). The major driver of the increase in GHG emissions was the increase of DDGS shares in the diets regardless of the allocation method used. However, the GHG emissions from market allocation were lower than those emissions from mass allocation because of reductions in carbon intensity of especially DDGS and soybean meal when market allocation was used. This is the result of the lower allocation ratio in the market value case compared to the mass allocation ratio, which required lower amounts of energy and material inputs for DDGS and soybean meal because of their lower market prices compared to those of ethanol and soybean oil, respectively (see SI Section S1).

Fig. 6. Greenhouse gas emissions of animal growth: market value vs. mass allocation for distiller-dried grains with solubles and soybean meal.

## 4. Discussion

As we presented in the results section, for both swine and poultry cases, the diet with the highest GHG and FFC values of animal feed corresponded to the diet with the largest DDGS content. This effect was transferred to the evaluation of the field-to-farm GHG emissions and FFC of animal growth. Because we used each of the diets presented in Table 2 as scenarios to illustrate how diet formulations influence swine and poultry production, the results of Fig. 3 are reflected in Fig. 4. Therefore, GHG emissions and FFC increased as more DDGS was added to the diets to take advantage to the economic benefits of adding DDGS (which increases the crude protein content in the final diet), while reducing corn and soybean meal composition. This could be attributed to DDGS having higher carbon intensity than soybean meal and corn (Fig. 2). AAs composition also changed with the diets; however, the amounts

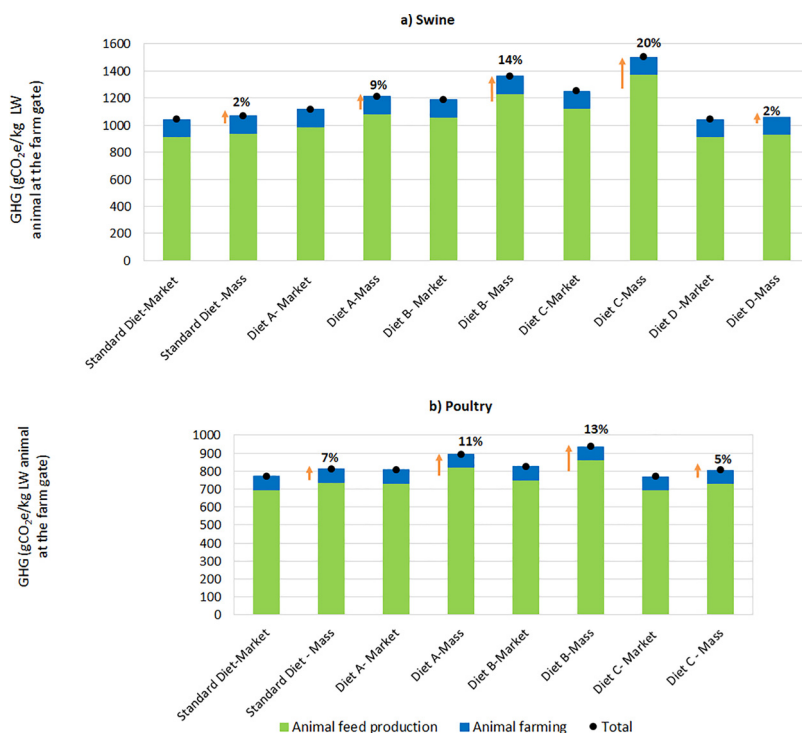


Fig. 6. Greenhouse gas emissions of animal growth: market value vs. mass allocation for distiller-dried grains with solubles and soybean meal.

were significantly lower than the other ingredients. Even though we found that AAs have the greatest carbon intensity per kg of ingredient among all the major components in these diets (Fig. 2), the biggest contributor to the GHG emissions during feed production, and the overall animal production process, was the DDGS. Therefore, as shown in Figs. 4,5, feed production was the major contributor to the life-cycle GHG emissions and FFC for swine and poultry production, accounting on average to 88 % and 91 % of the total GHG emissions and 79 % and 84 % of the total FFC, respectively. The results agreed with previous investigations in the literature where it was reported that the main contributor in the animal production supply chain was the feed production (Reckmann et al., 2013, 2016; Putman et al., 2017; Gonzales-Garcia et al., 2014).

As we discussed earlier, very few studies have explored the environmental impacts of diet variability in the animal production supply chain (Mosnier et al., 2011; Reckmann et al., 2016). Diet formulation was very different in each study, which makes the comparison to our results difficult. Mosnier et al. (2011), a European study, found that the incorporation of AAs to reduce the use of protein-rich ingredients in animal diets decreased environmental metrics such as eutrophication, ecotoxicity, and cumulative energy demand; however, the effect on GHG emissions depended on the source of protein-rich ingredients such as soybean meal. Mosnier et al. (2011) analyzed diets with soybean meal imported from Brazil, which had a significant environmental effect, as soybean meal imported from overseas was associated with deforestation. Therefore, substituting soy-based products that contributed to a high GHG-intensive supply chain improved the GHG emission profile. In contrast, the study presented here, with U.S. crop production, did not have the same effect when reducing soybean meal while slightly increasing some AA composition as compared to Mosnier et al. (2011). In fact, our results showed that GHG emissions increased mostly because of the significant increase of DDGS in the diets, which was slightly more GHG-intensive than soybean meal (Fig. 2). Despite the reduction in protein-rich ingredients like soybean meal in the diets, the crude protein level still increased as the level of DDGS increased due to the poorer protein quality of DDGS protein (see SI Section S3). While DDGS variability was considered in our study as being motivated by reducing the costs of the diets, it was not included in Mosnier et al. (2011). It is important to note that LCA results for animal production from other publications might be different and difficult to compare because of differences in the upstream input information used, such as fuel and energy sources, e.g., different electricity grids, alternative energy scenarios, the use of different LCA tools to evaluate impacts, different system boundaries, diet specifications, farming operation conditions, and overall goals of their analyses.

Water consumption, on the other hand, decreased as corn and soybean meal shares decreased in the diets because these two ingredients relied on water-intensive cultivation of corn and soybeans. The allocation methods used to assign the emission and energy burdens between DDGS and corn ethanol demonstrated the range of potential impacts. For instance, we found that life-cycle GHG emissions can decrease if we switched from the mass allocation method to the market-based allocation as the result of the reduced environmental footprint of DDGS, given its lower market value compared to that of ethanol. This suggested that the operation and environmental impacts of corn ethanol plants were driven by ethanol production more so than DDGS production. In addition, the carbon intensity of soybean meal improved when the market value allocation method was used because of its lower market price compared to soybean oil.

## 5. Conclusions

In this study, we conducted a life-cycle analysis of animal growth under different animal diets used in swine and poultry production to evaluate the environmental effects of the animal feed supply chain on animal growth when animal diets were formulated differently. It was found that the biggest contributor to life-cycle greenhouse gas emissions and fossil fuel consumption was sizable use of the distiller-dried grains with solubles as an ingredient. Other ingredient compositions were changed in the diets; however, they had less impact on the greenhouse gas emissions and fossil fuel consumption. For instance, amino acids, which had the greatest carbon intensity among all major ingredients (i.e., per kilograms of ingredient) for both swine and poultry diets, did not have a significant effect on greenhouse gas emissions and fossil fuel consumption because the use of amino acids was so small. However, reducing corn and soybean meal shares decreased water consumption, as these two ingredients relied on water-intensive cultivation processes. We also found that feed production played a major role in the life-cycle greenhouse gas emissions and fossil fuel consumption for swine and poultry production. While the replacement of soybean meal and corn with distiller-dried grains with solubles and amino acids can benefit the costs of animal production, as distiller-dried grains with solubles prices are very attractive, this switch could have a negative effect on the energy and environmental metrics such greenhouse gas emissions and fossil fuel consumption. Finally, there was a tradeoff between the energy and emissions resulting from animal production and the cost of formulating diets. The meat production industry needs to ensure that dietary requirements are met while minimizing environmental impacts without significantly impacting production costs. The new animal feed module in the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model will be publicly available and will allow stakeholders and users to edit the module to analyze their specific scenarios for formulating and using alternative animal diets.

### 5.1. Key sources of uncertainty and future work

We relied on the best public information available to obtain all the material and energy inputs needed for this analysis. However, certain parameters analyzed in this study can vary from farm to farm. For example, the type of diets, the source of energy used during farm operations, and manure quantities; and characterizations of different diets can be different among animal farms. Therefore, it is important to mention that this study is not necessarily representative of the current state of technology for the animal farming industry. One topic that can be explored in the future is the impact of manure production in the farm as the result of an increase of distiller-dried grains with solubles in the animal diets. The nitrogen content in manure increases as distiller-dried grains with solubles is increased in the diets. We discussed that using a protein such as that in distiller-dried grains with solubles has a lower proportion of a critical amino acid such as lysine; therefore, we need to supplement synthetic amino acid to meet animal nutritional needs. However, as one feeds more protein per unit of lysine, breaking down an excreting protein represents a metabolic expense to the animal as well as an environmental expense due to the excretion of more nitrogen from the proteins.

## Notes

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.anifeedsci.2020.114607>.

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