RESEARCH REPORT

ENVIRONMENT

Title: Carbon, water, and land use for pork production when modifying type and regional sourcing of feed ingredients – **NPB #17-128**

Final revised

Investigator: Dr. Jennifer Schmitt

Institution: University of Minnesota

Co-PIs: Dr. Pedro Urriola & Dr. Gerald Shurson

Date Submitted: September 6, 2018

Industry Summary

The current life cycle analysis of the environmental impacts of the pork industry developed for the National Pork Board (NPB) allows pig producers to calculate carbon, water and land footprint of their operations. However, feed ingredients and the environmental footprint that is associated with the production of these feed ingredients vary across the US. Likewise, manure management practices and the associated greenhouse gas emissions also reflect geographic and dietary variations. Therefore, the objective of this NPB funded project was to compare greenhouse gases (GHG), water, and land use of pork production when pigs are fed diets representing four alternative programs across regions of the U.S. For water and land, we looked at the impacts embedded in corn feed inputs on a per pig basis. For GHG emission we considered the lifecycle impacts of corn farming and pig manure production as well as emissions avoided from repurposing food waste, again on a per pig bases. For these impacts we created four feeding programs including: **1)** the use of corn distillers dried grains with solubles (DDGS) and **2)** dehydrated retail level food waste as approaches for recycling nutrients back into pig feed; as well as **3)** the use of synthetic amino acids and **4)** enzymes (i.e. phytase) as back-end diet supplementation strategies for minimizing the environmental impact of pork production. We developed these four feeding programs using nutrient composition and nutrient requirements from the National Research Council. These allowed us to formulate the diets using ingredients for three different regions across the US, and included the amount of corn in each feeding program from these regions. Corn production regions in the U.S. have different inherent environmental impacts, which we modeled using the Food Systems Sustainable Supply-chain model (FoodS^3) that uses county level environment impacts of corn production, rather than using a single national average estimate. We also added spatial difference in manure impacts by estimating the volatile solids excreted in manure by the three regional feeding programs using county specific manure management practices. Using these estimates, we calculated the water and land use impacts of corn and

DDGS in regional pig feeding programs, as well as the GHG impacts from corn inputs and manure emissions. Our results suggest that the use of synthetic amino acids had the greatest impact on dietary inclusion rates of corn, which increased from 190 kg/pig marketed in the Mid-West control diet to 239 kg/pig marketed in the Mid-West diet with synthetic amino acids. Conversely, use of corn in DDGS and food waste feeding programs was less than compared with using the control feeding program. Use of phytase also decreased utilization of corn (187 kg/pig). The consequence of greater use of corn in the synthetic amino acid feeding program increased the associated greenhouse gas emissions (92.45 kg CO_2 equiv./pig) compared with the control (74.40 kg CO_2 equiv./pig). Use of less corn in the food waste and phytase feeding programs decreased the associated greenhouse gas emissions to 51.25 and 72.16 kg CO_2 equiv./pig, respectively. Water use for growing corn used as the feed ingredient was greater in the feeding program using synthetic amino acids (16.91 m^3/pig) and phytase (12.02 m^3/pig) than control (11.58m^3/pig). Using the DDGS and food waste feeding programs decreased water use from corn input to 11.39 and 9.06 m^3/pig, respectively. Likewise, land use was reduced for the food waste (45.34 acres/1,000 pigs) and phytase (63.76 acres/1,000 pigs) feeding programs compared with the control feeding program (66.02 acres/1,000 pigs), but land use increased with the DDGS feeding program to 71.84 acres/1000 pigs. The increase in land use was due to the embedded corn in DDGS, to which we allocated 40.1% of all environmental impacts of ethanol production. This was an energy-based allocation following EPA guidelines. Intensity of GHG emissions for the control feeding program in the Mid-West (184.3 kg CO_2 equiv./pig) was less than the Mid-Atlantic (244.1 kg CO_2 equiv./pig) and Central regions (245 kg CO_2 equiv./pig). We observed that using the food waste feeding program resulted in the lowest corn input greenhouse gas emissions totals compared with all other feeding programs evaluated in this study. However, for all GHG emissions, the control feeding program had the lowest GHG emissions. While use of synthetic amino acids decreased excretion of volatile solids in manure, it resulted in the greatest greenhouse gas emissions. These emissions are the result of proportionally greater use corn in the synthetic amino acid diets than any other diet (more corn was required to ensure that the diet met the Nutrient Requirement for Swine (NRC, 2012) in our modeled diets). The impact of feeding program on greenhouse gas emissions also varied among geographic regions, where the Mid-West region had the least per pig emissions regardless of the type of diets used in the feeding program. This variation is primarily due to the spatially different emissions of feed ingredients estimated with our FoodS^3 model. As expected, water and land use were least for the feeding program based on food waste, while using synthetic amino acids in diets resulted in the greatest water and land use per pig produced. One important note, food waste was accounted for as true waste, thus we did not attribute the embedded impacts of production (for GHGs, water, and land use) to hog production. In conclusion, the results from this project suggest that the use of various feed ingredients and diet formulation strategies can result in different impacts on GHG, water, and land use. Therefore, U.S. pork producers can reduce the environmental footprint in pork production systems by selecting feed ingredients and managing the associated volatile solids in manure. These results show that pork producers can use feed ingredient selection and diet formulation strategies tailored to specific geographic regions of the U.S. to have even greater positive environmental impacts. However, future research is needed to determine the complete life cycle environmental impacts of all feed ingredients, supplements, and diet formulation strategies.

In summary, the results from this research suggest:

1. Greenhouse gas emissions resulting from corn used in pig diets have a large impact on the carbon footprint of pork production. Pork producers could displace corn with less

carbon intensive feed ingredients, but alternative ingredients need evaluation. Likewise, pork producers can encourage corn producers to use practices that reduce the carbon footprint of corn production.
2. Although the type of feeding programs used in each region, affects environmental impact, the associated manure management practices implemented have a greater impact. Therefore, pork producers should implement best manure management practices that are suited to each region.
3. Future LCA research should focus on analyzing feeding programs that combine all factors evaluated in this project to estimate the environmental impacts of all the dietary ingredients commonly used in commercial pig diets.

For more information, please contact Jennifer Schmitt: jenniferschmitt@umn.edu

Keywords
Pig diet, feed formulation, environmental footprint, food waste, amino acid, enzyme

Scientific Abstract

Major food companies, including the largest pork producer in the US, have initiated supply chain management programs to minimize their carbon footprint in response to consumer demands and societal concerns. One area highlighted for continued improvement is animal feed, which is the second largest impact category for pork production. We have created a hotspot LCA analysis focused on four pig diets: DDGS, Food Waste, Synthetic AA, and Inorganic P. We compared these four alternative diets to a control diet of corn and soy for three regions in the US (Mid-West, Central and Mid-Atlantic), using our Food System Supply-chain Sustainability model ($FoodS^3$) to incorporate county specific differences for environmental impacts. We found that a diet using processed food waste has the lowest land and water impact, while the control diet has the lowest GHG impact. We also found that the Mid-West has the lowest GHG impact diets, across diet formulations, the Mid-Atlantic has the lowest water footprint across diet formulations, and the Central diet has the lowest land impacts for all but one diet formulation. However, a complete LCA analysis, including production impacts from all feed ingredients is needed to determine the "best" diet from a carbon, water, and land perspective. Furthermore, work in this area needs to move beyond changing one ingredient to analyzing variations of complex feed. Most commercially available diets in the US contain synthetic AA and inorganic P and many include DDGS. Any changes to production systems must consider the concurrent effects on pig growth, meat quality and economics. With increasing focus on sustainability, both changes to inputs and changes in production systems must consider the effect on environmental impacts. However, determining what changes to feed inputs are truly sustainable remains an ongoing question.

Introduction

Providing animal protein to tomorrow's nine billion people will be a challenge given the associated environmental pressures with animal production, particularly issues such as greenhouse gas (GHG) emissions, human health, and water usage/quality. The United Nations has called on the international community to focus on feeding a growing population while minimizing food's environmental impact in Millennium Development Goals (United Nations, 2015). Finding ways to produce animal protein while reducing the associated environmental impacts is vital to maintaining the long-term economic viability and cultural significance of this industry. The US Pork Industry clearly has a path to meet this objective. Continuing to be on the forefront of sustainable protein research and advancing ways for the pork industry to maintain production while reducing environmental impacts will lead pork to not only be the other white meat, but the meat of choice for its input flexibility and low environmental impact.

There is tremendous need to evaluate opportunities to improve environmental sustainability of pork production. This is an emerging and critical area that is in need of extensive research because of the "upstream" and "downstream" role that pork production plays on the environment and natural resource use. Major food companies have initiated supply chain management programs to minimize their carbon footprint in response to consumer demands and societal concerns. Globally, livestock production systems contribute 14.5% to the total human-induced emissions of greenhouse gases (FAO, 2013). Animal feed is a major component of environmental sustainability of livestock production systems, and the composition of animal diets has important downstream effects (i.e. GHG emissions, animal productivity, animal health, product safety and quality, and animal welfare) as well as upstream effects on water quality, GHG emissions, land use, and energy consumption (Makkar, 2016). The production, processing, and transport of feed represents 45% of GHG emissions from livestock production systems (FAO, 2013).

Commercial pork production operations are a critical part of this "farm to table" life cycle analysis for improving environmental sustainability. To objectively evaluate these operations, it is necessary to use a systems based understanding of the impact that alternative feeding programs have on pork production productivity and profitability as well as the impact on greenhouse gas (GHG), water, and land use. Dietary modifications are most likely to help mitigate negative environmental impacts of pork production because diets are a major contributor to the GHG and water use of pork production (~35% of all GHG emissions and >80% of all water use occurs in hog feed LCA category) (Thoma et al., 2011; Matlock et al., 2014). Approaches are beginning to be developed to evaluate the environmental impact of animal feeds and feed ingredients. A sustainable animal diets concept has been developed by FAO, which involves using several planets, people, and profit indicators of sustainability (van Holsteijn et al., 2016). Mackenzie et al. (2016) conducted a Life Cycle Assessment of the environmental impact of several feed ingredients in Canadian pork production systems based on their acidification potential, eutrophication potential, global warming potential, nonrenewable energy use, and nonrenewable resource use. We are unaware of similar studies conducted relative to the impacts of using various feeding ingredients and feeding strategies in the U.S. pork industry. Therefore, ***this project focuses on two alternative feed formulations that recycle nutrients back into pig feed and two that replace corn and soybean meal by back-end displacement using amino acids or enzymes.***

Feeding programs for growing and finishing pigs have focused on cost minimization as well as productivity (Pomar et al., 2007; Dubeau et al., 2011). The meat industry in general has become a focal point in sustainability discussions due to its high environmental input (Foley et al., 2011; Cassidy et al., 2013). Feed grains are one of the largest GHG, water, and land use contributors to pork production (Thoma et al., 2011; Matlock et al., 2014). The same general story is true for other meat industries. There are some aspects associated with environmental impact that are difficult to change (i.e. biological limits of feed conversion and manure gas emissions), which makes pork production intermediate between chicken and beef (Shepon et al., 2016). However, pigs have a competitive advantage with these food animal species because the composition of their diets are somewhat more accommodating to high fiber ingredients than poultry diets, and they are not as input intensive as cattle (Zijlstra & Beltranena, 2013). This provides the U.S. pork industry an opportunity to potentially change the environmental impacts of their product, thereby creating the possibility of pork becoming known as the "sustainable white meat".

While significant research has been conducted to evaluate the benefits and limitations of feeding corn distillers dried grains with solubles (DDGS) to hogs, there is very little information on its environmental impacts on pork production systems (Shurson, 2017). In the U.S., about 40% of the annual food produced (60 million metric tonnes) is lost at the retail and consumer levels (Buzby and Hyman, 2012), which contributed to the high cost of food and is a significant cost ($165 billion) to the U.S. economy (Gunder, 2012). The U.S. Environmental Protection Agency has suggested that recycling food waste into animal feed in the most preferred method (after source reduction and feeding hungry people) compared with industrial uses, composting, and landfill/incineration. Disposal of food waste in landfills increases greenhouse gas emissions while composting results in loss in economic and nutrient value. Therefore, significant opportunities exist to recycle food waste into animal feed to capture valuable energy and nutrients, reduce cost, and improve environmental sustainability. Enzymes (e.g., phytase and carbohydrases) as well as synthetic amino acids have been widely used to mitigate the impact of diet composition on excretion of nutrients. However, there are no reports that integrate the impact of these alternative programs with LCA analysis for US pork production. More importantly, there are no LCAs that have evaluated the regional aspects to diet formulation. The environmental impact of corn and soybean production vary across the US, suggesting that alternative feed options are more nuanced than current considerations suggest. Therefore, the current project leverages experience at UMN on an existing spatially explicit feed input model for pork production in the US. The US pork industry is not a homogenous group of producers (in location, size, or even feed inputs) and therefore providing one single LCA number for the entire industry is incomplete.

Objectives

The overall goal of this project was to compare carbon, water, and land use of pork production when pigs are fed traditional corn-soybean meal diets and diets containing alternative ingredients. This project provides the U.S. pork industry with sustainability criteria to minimize environmental impacts when formulating pig diets. We did this by exploring two alternative feeding programs that recycle nutrients back into diets for growing pigs to alter the environmental impact of feed inputs, and two feeding programs that use "back-end" strategies for minimizing the environmental impact of manure. In our comparative life cycle analysis (LCA), we also incorporated a spatial component, which not only allowed us to provide an average comparison between alternative feeding programs, but also provide a regional comparison across diet alternatives. More specifically, the objectives of our study were to:

1) Assess the environmental impact of using four alternative feeding programs, two of which represent "front-end" recycling of nutrients and two of which represent "back-end" strategies to reduce environmental impacts of pork production.
2) Compare the costs of the four alternative feeding programs with traditional corn-soybean meal diets.
3) Highlight the differences in greenhouse gas (GHG) estimations, water use, and land use associated with pork production under the four alternative programs.

4) Provide spatially explicit regional estimates of costs and environmental impacts of the four alternative feeding programs.

The four alternative feeding programs included 1) the use of corn distillers dried grains with solubles (DDGS) and 2) dehydrated retail level food waste as mechanisms for recycling nutrients back into pig feed, as well as 3) the use of enzymes (i.e. phytase and carbohydrases) and 4) synthetic amino acid additions as back-end strategies for minimizing the environmental impact of pork production. All four feeding programs partially replace some of corn, soybean meal, and inorganic phosphorus in the diets. They also affect manure composition. Furthermore, corn and soybean meal use, GHG emissions, as well as water and land use in the United States are not homogenous across the country (Smith et al., 2017). The variability in the environmental impact of different pig diets and the estimated spatially explicit corn and soybean meal being displaced by alternative diets will change the cost and environmental impact estimation for pork producers in different regions of the country.

Materials and methods

Feed formulation

Assessment of environmental impact for growing-finishing pigs were performed using an attributional LCA approach, which aims at providing spatially explicit, regional estimates of costs and environmental impacts of the four alternative feeding programs. We formulated 60 simulated diets, considering five scenarios (four feeding programs plus one control), four phases over the growing-finishing period, and three different regions on a least cost basis. We used data on ingredient cost from the Feed Grains Custom Query for 2017 (ERS, 2017). The front-end modifications to diet sourcing inputs corn DDGS and food waste, while the back-end modifications were inclusion of synthetic amino acid (AA) and enzymes (phytase, 500 FTU / kg). We divided the diets for growing-finishing pigs according to their stage of growth: phase 1 (from 25 to 50 kg BW), phase 2 (from 50 to 80 kg BW), phase 3 (from 80 to 105 kg BW), and phase 4 (from 105 to 130 kg BW). To represent regional variations in pig diets we created three geographical divisions (Mid-West, Central, and Mid-Atlantic) using USDA databases (USDA NASS, 2018), as well as previous research of Klasing (2012). For feed formulation, we used common practices of ingredient evaluation in North America. These are the use of amino acids digestible in the terminal ileum (standardized ileal digestible amino acids; SID AA), metabolizable energy (ME), and apparent total tract digestibility (ATTD) of phosphorus requirements with the same content between treatments, within each phase. We then use the National Swine Nutrition Guide diet formulation and evaluation software (NSNG, 2010) to generate each treatment of diets, specifically matches the recommended requirements from the Nutrient Requirement for Swine (NRC, 2012). The control diet was a simplified typical corn-soybean meal growing-finishing pig diet for U.S. feed systems, which contained none of the co-products or the additives we used for the alternative dies. Finally, we formulated all diets with respect to the currently accepted limits of maximum inclusion levels for different feed ingredients, as described below.

1. *Corn Distillers Dried Grains with Solubles (DDGS)*

DDGS are a co-product of the corn ethanol industry, produced in the fermentation process of starch from cereal grains in dry mill ethanol plants (Aines et al., 1986). DDGS have become the most popular, economical and widely available alternative feed ingredient for use in U.S. pig diets in all phases of production (Salim et al., 2010). Several researches (Stein and Shurson, 2009; Wu et al., 2016; Zeng et al., 2017) suggest that DDGS can primarily replaces a portion of the corn when added to pig diets due to the same amount of metabolizable energy

(ME) as corn. Moreover, DDGS can be included up to 30% of growing-finishing diet with no detrimental effects on performance (Jacela et al., 2011; Wu et al., 2016; Coble et al., 2017). There can be effects of DDGS inclusion on product quality; however, evaluating such effects was outside the scope of this work.

2. *Food waste (FW)*

As part of a project on recycling food waste, we had nutritional information and digestibility for three dehydrated sources of food waste (i.e., fish waste, grocery store waste, and fruit and vegetable waste). These sources of food waste represent pre-consumer and retail level food waste. We collected food waste from these sources, all of which represent future supplies of nutrients available to pork producers in the US. The chemical analysis was done by the University of Missouri Agricultural Experiment Station Chemical Laboratories (Columbia, MO) (AOAC Int., 2006), while the energy content, amino acid (AA) digestibility, apparent total tract digestibility (ATTD) of phosphorus were determined throughout *in vivo* metabolic trial for growing pigs ranged 25 to 50 kg of body weight (Fung et al., 2018). Given the variability in food waste sources and nutritional values, we averaged the food waste results to represent one composite, mixed food waste input, adding it to the feedstuff library of formulation software (NSNG, 2010). We based our justification of the maximum inclusion levels used for each dietary phase for the food waste on relative nutritional values compared with high protein ingredients (e.g. fish meal, blood and bone meal, and skim dried porcine protein), as well as advice from industry experts working on feed formulation.

3. *Synthetic Amino Acids (CAA)*

To reduce the crude protein (CP) content and nitrogen (N) intake of the pigs we modeled our third diet using synthetic AA. The reduced CP content is expected to reduce the N excretion of pigs, thus influencing the total environmental impact of pork production. Recent LCA studies evaluating nutritional strategies for growing-finishing pig diets have suggested that partially replacing SBM with CAA is an effective nutritional strategies for improving the environmental performance of pig production, especially in decreasing global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP) (Ogino et al., 2005; Garcia-Launay et al., 2014; Monteiro et al., 2017).

4. *Phytase (P)*

The use of phytase in diets for growing pigs have been one of the greatest tools for modifying diet and manure composition (Lei et al., 2013). Using the phytase enzyme consistently decreases the use of organic phosphorus in diets for growing pigs (Veum et al., 2006). phytase sources and their respective activity levels are indicated with the available phosphorus and ATTD phosphorus release values at each inclusion level (500 FTU / kg; Phyzyme® XP; Danisco Animal Nutrition, Marlborough, UK). We used data from Simons et al. (1990) and Jones et al. (2010) to develop the available phytase release curve.

Estimation of animal growth and excreta

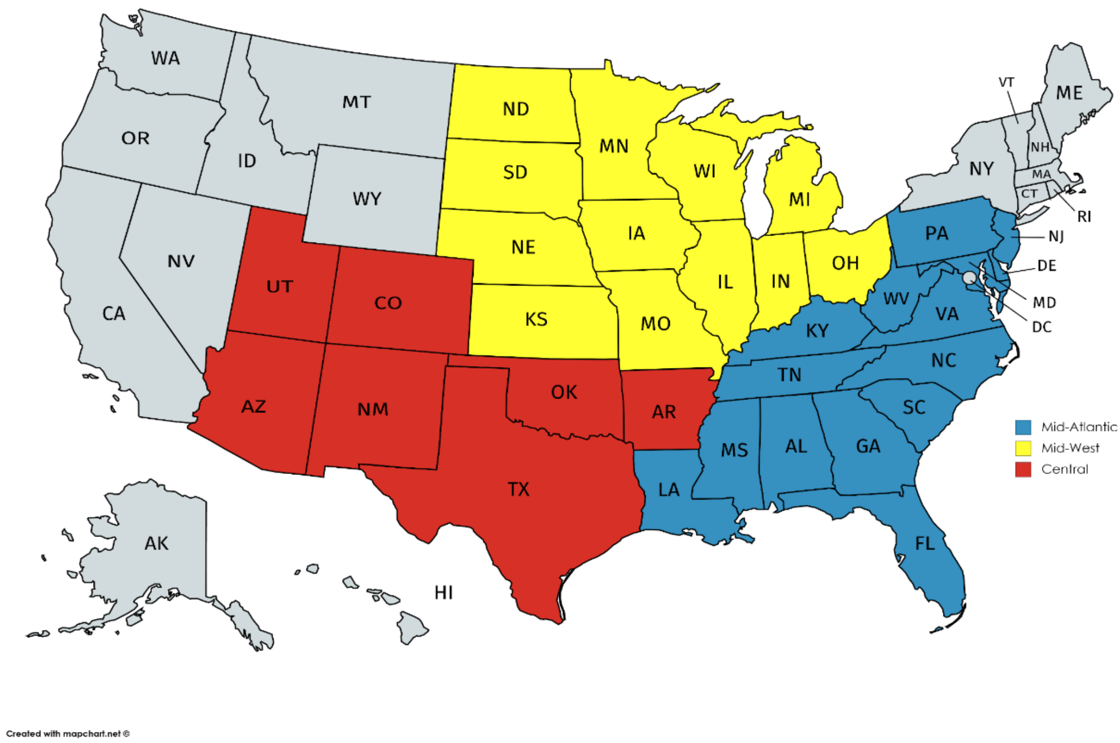
Based on the feed formulation, we simulated animal growth rate and performance using the NRC equations (National Research Council, 2012). The nutrient database and formulation module allowed us to compare the amounts of nutrients supplied in specified feeding programs with estimated requirements. Depending upon the nutrient factors, the model predicts nitrogen, phosphorus, and carbon excretion both in urine and feces into the environment in each growth stage of pigs. We based our calculation of Volatile Solids (VS) produced in manure on the equation provided by IPCC (2006) described as:

$$VS = [GE \times (1 - DE\ \% / 100) + (UE \times GE)] \times [(1 - ASH) / 18.45]$$, where

VS = volatile solid excretion per day on a dry-organic matter basis, kg VS /day.
GE = gross energy intake, MJ per pig.
DE = digestibility of the feed in percent.
UE = urinary energy expressed as fraction of GE (assumed to be 0.02).
ASH = the ash content of manure calculated as a fraction of the dry matter feed intake.
18.45 = approximate conversion factor for dietary GE per kg of dry matter (MJ kg-1).

Regions
We provided a regional estimation of pig diets, allowing for variations in feed ingredients to more accurately reflect pig diets in the region. The three regions we used in the study are Mid-West, Mid-Atlantic and Central, covering almost 98% of all pig production (Figure 1). We did not report diets for the pigs outside these regions, but needed to assign them a diet in order to run our feed sourcing model (described in Environmental Impacts). For the pigs outside these three regions we assumed a Mid-West diet.

Figure 1: Regions of pig diets



Environmental Impacts
In order to assess the environmental impacts of the feeding programs we focused on the two largest hotspots of GHG emissions, corn feed inputs and manure management. We also considered avoided impacts from both energy production from anaerobic digestion of manure and in preventing food waste from being landfilled.

1. Corn Feed Inputs
Our assessment of the environmental impacts of corn feed ingredients is based on a spatially explicit, US model of corn movement (Smith et al., 2017). This model, the Food System

Supply-chain Sustainability Model (FoodS^3) considers the cradle to farm gate (i.e. from raw material extraction of all inputs through pig production) impacts for corn production at the county level. We used spatialized GHG impacts at the county level as described in Pelton (2018). These impacts are based on 2012 production and consumption data. In this stage of inputs, we also included the impacts from the use of DDGS by accounting for the additional energy required to produce DDGS and the embedded corn in the DDGS product. We follow the original allocation of impacts in Smith et al. (2017) and based allocation on energy, which leads to 40.1% corn environmental impacts being allocated to DDGS. We also use the water impacts in Smith et al. (2017) to measure irrigated water use at the county level. Finally, we have added land to the FoodS^3 model for this project, summing up the land acres required to grow the corn used in the pig diets.

2. Manure Management

Beyond corn feed inputs, we also considered the GHG impacts of manure management as it is the largest hotspot of GHG emissions (Thoma et al., 2011). To account for manure management at a county scale we used the methodology of Pelton (2016). We used state level manure management types and assumed county level manure management reflected the state distributions. We accounted for average county ambient temperatures and altered the county manure management distributions to account for counties that have documented usage of anaerobic digesters that are operational based on information provided by the EPA's AgSTAR database (EPA, 2014; EPA, 2016b). For the anaerobic digester systems, the methane captured is either flared (i.e. combusted without energy recovery) or is converted to thermal energy and/or electricity typically for use on the farm (EPA, 2010), and are dependent on overall collection efficiency assumptions (EPA, 2016). Accounting for these different manure management systems, including anaerobic digesters, allowed us to account for spatial differences in manure management mixes, applied to 2012 hog numbers.

We recalculated the emissions for the manure based on both nitrogen and volatile solid levels for each diet formulation, using a life cycle approach to accounting for manure emissions. We integrated the quantity of volatile solids and nitrogen produced throughout each successive growing phase over the pig's lifetime, corresponding to a finished hog mass of 268 pounds (Thoma, et al., 2011; EPA, 2016). In addition, following best practice methods, we allocated a portion of the manure emissions generated from breeding sows to each hog based on the average number of litters and number of piglets per litter, assumed to be approximately 3.5 litters and 9.5 piglets per litter, respectively (Thoma, et al., 2011). Due to the lack of data regarding inter-county transport of pigs within different growing stages, our model assumes that total lifetime manure is handled in the county in which the hog is sold/supplied to the processing facility.

3. Avoided impacts

Landfilled food waste generates GHG emissions that have large environmental impacts. Therefore, the environmental impacts of our LCA analysis considered the GHG emissions prevented by diverting food waste away from landfill. We used a single estimate for the avoided emissions across the US, as we do not have a spatially explicit model of food waste sourcing available to mimic the FoodS^3 corn-sourcing model. For this single estimate we used the EPA's WARM model assumption of a composite food waste mix (meats and other foods) and their estimation that there is a net emission of 700 kgCO2e[1] per short ton of food

---

[1] CO2e stands for carbon dioxide equivalent, which is a standard unit that converts the impact of different greenhouse gases into the amount of CO2 that would create the same amount of warming.

waste. This value includes transportation of food to landfill, methane emissions from landfilling and carbon savings from landfill carbon storage. We use this value as the avoided impacts of using food waste in the hog diet. We did not attribute the embedded impacts (GHG, water, or land) from the production of the food to hog production, considering food waste as waste and not a byproduct.

Results

Feed formulation

For each of our analyzed diet formulations we added one addition to the control diet, causing all other control ingredients to vary, ensuring our diet formulations met or exceed the NRC (2012) requirement. These diet variations caused corn feed inputs to change, altering a key environmental hotspot ingredient (Table 1). Food waste and phytase inclusion did not vary by region, but were included at 22.71, kg/market pig and 0.23 kg respectively. We did not vary DDGS by region either, including it at 70.75 kg for the DDGS diet and zero otherwise. Synthetic AA did vary by region and was included at some level in all diets, with an average intake of 3.80 kg/market pig. The complete diet formulations are in Appendix A.

Table 1: Corn feed inputs by region (Unit: kilogram)

Region	Control	DDGS	Food waste	Synthetic AA	Inorganic P
Mid-West	190.20	120.85	127.78	238.92	186.65
Mid-Atlantic	198.84	107.50	143.25	230.08	171.39
Central	176.79	112.28	136.15	226.40	170.70

The costs of the diets varied across formulation and region. For the Mid-West and Mid-Atlantic, the food waste diet was cheapest while the DDGS diet was cheapest for the Central region (Table 2). The most expensive diets for the Mid-West and Mid-Atlantic were the synthetic AA diets, while the control diet was slightly more expensive than the synthetic AA diets for the Central region. The cheapest diet overall was the food waste diet in the Mid-Atlantic, which was 11% cheaper than the most expensive diet of synthetic AA, also in the Mid-Atlantic.

Table 2: Feed price of pig diets by region ($/ton)

Region	Control	DDGS	Food waste	Synthetic AA	Inorganic P
Mid-West	$204.50	$191.91	$189.74	$205.58	$203.26
Mid-Atlantic	$203.44	$184.06	$181.45	$207.42	$206.36
Central	$204.94	$183.68	$185.48	$204.16	$202.39

Environmental Impacts

The environmental impacts of each diet varied across regions, diets, and impacts. Total environmental impacts are listed in Appendix B, below we present the per hog environmental intensity impacts. For water and land use the only stage in the supply chain we measured impacts was the corn farm (including corn embedded in DDGS). For GHGs we look at emissions in three areas, corn farming, manure management, and prevented food waste.

Water use per hog was the lowest for the food waste diet within all regions while the synthetic AA diet has the largest water use (Table 3). The supply chain impacts of corn sourcing are evident in much larger water use values for the Central region, which our model suggest is pulling corn from more irrigated areas. This results in estimated water use intensity levels in the Central region that are around ten times or greater than the Mid-West and Mid-Atlantic regions, across all diet types.

Table 3: Per hog water use from corn feed inputs, including corn farming and DDGS, by region (m^3/pig) and weighted total

Region	Control	DDGS	Food Waste	Synthetic AA	Inorganic P
Mid-West	8.21	8.09	5.62	10.48	7.94
Mid-Atlantic	2.25	2.52	1.73	3.35	1.90
Central	69.78	67.82	63.07	117.58	79.63
Total US	11.58	11.39	9.06	16.91	12.02

Similar to the water use findings, the food waste diet has the lowest land use per pig, while the synthetic AA has the largest (Table 4). The lowest acre use per pig occurs for pigs fed a food waste diet in the Central region.

Table 4: Per pig land use from corn feed inputs, including corn farming and DDGS, by region (acres/1,000 pigs*)

Region	Control	DDGS	Food waste	Synthetic AA	Inorganic P
Mid-West	66.65	72.61	45.25	83.62	66.29
Mid-Atlantic	66.15	72.19	46.46	76.82	55.94
Central	59.18	62.89	43.60	71.55	56.55
Total US	66.02	71.84	45.34	81.55	63.76

*Note the units here are different from other tables in order to show the variation across regions and diets.

While the hotspots of water and land are largely in the corn farming stage, GHG emissions are also significant for manure management. Furthermore, one key motivation for using food waste in pig feed is finding alternatives to landfilling, which also has significant GHG emissions. Therefore, for GHG emissions we have multiple supply chain stages of emissions. When only looking at the GHG emission intensities at the corn feed input stage, the food waste diet had the lowest GHG totals in each region (Table 5). The synthetic AA diet has the largest GHG intensities for the corn farming stage in the Mid-West and Central regions, but the DDGS diet is slightly larger than the synthetic AA diet for the Mid-Atlantic region.

Table 5: Per pig GHG emissions from corn feed inputs, including corn farming and DDGS, by region (kgCO2e/pig)

Region	Control	DDGS	Food Waste	Synthetic AA	Inorganic P
Mid-West	74.66	81.23	50.65	93.94	74.37
Mid-Atlantic	73.24	85.45	51.54	84.90	61.71
Central	74.53	77.43	56.84	95.56	74.79
Total US	74.40	81.70	51.25	92.45	72.16

When we look across all the supply chain stages measured in this study, the control diet, if applied to all pigs in the US has the lowest GHG intensities (Table 6). The pig diet with inorganic P has emission levels close to the control diet and the DDGS diet has the largest total GHG emissions. These totals equate to per pig GHG intensities of 199.2, 259.8, 209.7, 221.1, 201.0 kgCO2e / pig for the control, DDGS, food waste, synthetic AA and inorganic P diets respectively.

Table 6: Total GHG emissions from pig diets (MTCO2e)

Emission Hot Spots	Control	DDGS	Food Waste	Synthetic AA	Inorganic P
Corn feed inputs	8,498,275	9,332,197	5,853,907	10,560,160	8,242,235
Manure management	14,257,282	20,344,477	20,099,539	14,696,977	14,714,305
Avoided Food Waste Emissions			-2,001,559		
Total	22,755,557	29,676,674	23,951,886	25,257,137	22,956,540

Breaking these emissions down across regions we find that from a per pig perspective, the least GHG intensive diet is a control diet in the Mid-West at 184.3 kgCO2e per pig (Table 7). The inorganic P and food waste diets in the Mid-West region are the second and third lowest GHG intensive diets respectively. While the GHG intensities vary among regions, within the diets the Mid-West is always the lowest intensity, followed by the Central region with the Mid-Atlantic having the highest per pig GHG intensity. Within the regions, the diet intensities are always lowest for control and then inorganic P and highest GHG intensity in the DDGS. However, the food waste diet has a lower GHG intensity than the synthetic AA diet in the Mid-West, but it is greater than the synthetic AA diet for the Mid-Atlantic and Central regions.

Table 7: Per pig GHG intensity from pig diets by region (kgCO2e/pig)

Region	Control	DDGS	Food Waste	Synthetic AA	Inorganic P
Mid-West	184.3	219.2	188.3	209.4	184.5
Mid-Atlantic	244.1	418.9	279.9	260.1	252.0
Central	245.3	293.2	260.4	247.9	247.6
Total US	199.2	259.8	209.7	221.1	201.0

Discussion

The environmental impacts of pig diets in this study addressed the two largest hotspots of pork production GHG impacts, manure and corn inputs. The Pig Production Environmental Footprint Calculator considers the GHG, water, and land impacts of various diets. However, it lacks the spatial heterogeneity that exists in US pork production (Smith et al., 2017; Pelton, 2018). We have brought that spatial heterogeneity into the analysis for four alternative pig diets, DDGS, food waste, synthetic AA and inorganic P. To compare impacts, we evaluated each diet with just the one ingredient changing from a control diet of corn and soy. We did this for three regions in the US and found that a diet using processed food waste has the lowest land and water impact, while the control diet has the lowest GHG impact. We also found that the Mid-West has the lowest GHG impact diets, across diet formulations, the Mid-Atlantic has the lowest water footprint across diet formulations, and the Central diet has the lowest land impacts for all but one diet formulation.

The inclusion of county level spatial environmental impact data and supply chain connections are novel to this work. Location matters, not just in regional diet mixes, but also in environmental impacts of sourcing ingredients and manure management. With the FoodS^3 model is was possible to bring in modeled supply relationships in environmental impact analysis. Similarly, having food waste data nutrient analyses available to test a food waste diet added in a hypothetical “future technology” for pig food that has not been extensively studied.

Bringing food waste into the analysis (and any other co-product or waste, including DDGS) complicates the environmental impact assessment. For food waste, given it has no commercial value, there are environmental gains to the system through preventing landfilled methane emissions. Furthermore, as a waste, the embedded GHG, water, and land impacts are not attributed to hog production. However, if food waste becomes a co-product, embedded environmental emissions would arguably be allocated to pig feed, changing the overall allocation of the food waste impacts. To illustrate this point we discuss the co-product DDGS and how we treated it in this analysis.

Originally, DDGS were considered a waste or byproduct of ethanol production. Inclusion of DDGS in pig feed was considered a win-win because it prevented landfilling DDGS. However, as the ethanol industry has matured, DDGS have become a significantly valued co-product. In this case, LCA analysis allocates some of the environmental impacts of ethanol production to its co-products, i.e. DDGS. Allocation typically occurs on a mass, energy or economics basis. For product processes that produce multiple fuel energy products, the EPA recommends impact allocation based on the relative energy content of the fuels, as this reflects the 'use' of the product. Following this, and the original allocation of Smith et al. (2017), we used the relative energy content for our allocation of impacts to DDGS. Using a mass allocation would have attributed a similar percentage of impacts to DDGS. However, the third allocation method, based on relative economic relationships between product outputs would suggest an allocation of 19.9%. At this level of allocation, the overall land water and GHG impacts decrease to levels below the control group values (Appendix C). While improving the DDGS diet footprint, the economic allocation does not change the general story of lowest and highest impact diets. Even though all DDGS corn input impacts are better, the supply-chain greenhouse gas emissions per pig remain highest for DDGS diet, dropping to 242.2 kgCO2e/pig with the economic allocation.

Ultimately, whether any environmental impacts are considered, and how much of the impacts are associated with co-products, is a matter of policy and allocation, not science. The EPA has adopted the International Standards Organization (ISO) allocation hierarchy for defining the appropriate allocation scheme for use in the assessment of biofuel GHG compliance (Wang et al., 2011). This requires the allocation of some environmental impact to DDGS. More importantly to making decisions on pig diets is doing a complete LCA analysis, rather than a hotspot analysis. We considered production impacts of GHG emissions for DDGS because they were part of the $FoodS^3$ model. However, there will be production emissions from the other alternative diet ingredients. Including full production impacts for the diet alternatives would increase the total GHG emissions associated with these three diets. Whether the total GHG emissions per pig of the food waste, synthetic AA, or inorganic P diet would become greater than the DDGS diet is unknown until a complete LCA of these ingredients is performed. Water and land impacts associated with the production of the alternative diet ingredients are likely small and therefore are unlikely to change our overall assessment of diets and regions for these impacts, but they too were not part of this study.

Along the same lines of including the full LCA impacts of the production of diet alternatives is the need to do a complete LCA of the diets, looking at the environmental impacts of all the ingredients, not just corn, DDGS, and food waste. The inclusion of soy will alter the land, water, and carbon impacts, yielding reductions in the synthetic AA diet impacts because that diet does not include soymeal. A complete feed mix LCA would also improve the comparative impact of the DDGS diets, especially in the Mid-Atlantic and Central regions where soymeal in DDGS diets is lower than the other diets (except the synthetic AA diet). We would also expect relative changes in the comparative diet impacts with the inclusion of wheat middlings. Wheat uses significant land, water, and land inputs, some of which we would allocate to the middlings in the same manner that we allocated impacts to DDGS. We do not know how the addition of the environmental impacts of the low inclusion ingredients will affect the comparisons of the diets, though limestone is likely to have significant GHG emissions. A complete feed mix LCA, inclusive of all ingredients would show the “best” diet from a carbon, water, and land perspective.

While this study was an important step in bringing spatial heterogeneity to understanding the environmental impacts of pig diets, further work should consider diets with combinations of our alternative ingredients. Most commercially available pig diets already include synthetic AA and inorganic P, and many include DDGS. Furthermore, the diets may have regional variations in more than just corn and soy (which we accounted for), but also in some of our alternative ingredients, such as DDGS and food waste. Future research is needed to compare the environmental impacts of these diets to one that includes food waste as well as examine different rates of inclusion for food waste.

References

Aines, G., T. Klopfenstein, and R. Stock. 1986. Distillers Grains, Historical Materials from University of Nebraska-Lincoln Extension, University of Nebraska Cooperative Extension Report, MP 51.

AOAC International. 2006. Official methods of analysis of AOAC International. 18th ed. AOAC Int., Arlington, VA.

Buzby, J. C., & Hyman, J. (2012). Total and per capita value of food loss in the United States. Food Policy, 37(5), 561–570. https://doi.org/10.1016/j.foodpol.2012.06.002

Cassidy, E. S., West, P. C., Gerber, J. S., & Foley, J. A. (2013). Redefining agricultural yields: from tonnes to people nourished per hectare. Environmental Research Letters, 8(3), 34015. https://doi.org/10.1088/1748-9326/8/3/034015

Coble, K. F., J. M. DeRouchey, M. D. Tokach, S. S. Dritz, R. D. Goodband, and J. C. Woodworth. 2017. Effects of distillers dried grains with solubles and added fat fed immediately before slaughter on growth performance and carcass characteristics of finishing pigs. Journal of animal science 95, 270-278.

Dubeau, F., Julien, P.O., Pomar, C., 2011. Formulating diets for growing pigs: economic and environmental considerations. Ann. Oper. Res. 190, 239e269. http://dx.doi.org/10.1007/s10479-009-0633-1.

Economic Research Service. 2017. Feed Grains Custom Query. United States Department of Agriculture. Washington D.C. https://data.ers.usda.gov/FEED-GRAINS-custom-query.aspx#ResultsPanel.

EPA, 2010. *U.S. Farm Anaerobic Digestion Systems: A 2010 Snapshot..* s.l., United State Environmental Protection Agency.

EPA, 2014. *AgSTAR National Mapping Tool.* Available at: http://www.epa.gov/agstar/tools/map/index.html

EPA, 2016. *Title 40, Part 98, Subpart JJ: Protection of Environment, Mandatory Greenhouse Gas Reporting, Manure Management.* Available at: www.ecfr.gov/cgi-bin/text-idx?SID=6bdcd18c7ed3ebf214e4acffc2dc60c8&mc=true&node=sp40.21.98.jj&rgn=div6

EPA, 2016b. *Methdological descriptions for additional source or sink categories, annex 3-Part B, section 3.11.* Available at: https://www.epa.gov/sites/production/files/2018-01/documents/2018_annex_3_-_part_b.pdf

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., … O'Connell, C. (2011). Solutions for a cultivated planet. Nature, 478(7369), 337–42. https://doi.org/10.1038/nature10452

Food and Agricultural Organization of the United Nations (FAO) (2013) Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities (FAO, Rome). Available at www.fao.org/3/a-i3437e/index.html. Accessed January 5, 2016.

Fung, L, PE Urriola, L Baker, GC Shurson. 2018. Estimated energy and nutrient composition of different sources of food waste and their potential use in sustainable swine feeding programs. Transl Anim Sci TAS-2018-0185 (accepted).

Garcia-Launay, F., H. M. G. Van der Werf, T. T. H. Nguyen, L. Le Tutour, and J. Y. Dourmad. 2014. Evaluation of the environmental implications of the incorporation of feed-use amino acids in pig production using Life Cycle Assessment. Livestock Science 161, 158-175.

Gunders, D. 2012. Wasted: how America is losing up to 40 percent of its food from farm to fork to landfill, Issue Paper IP:12-06B, Natural Resources Defense Council (NRDC), New York, NY, USA.

Jacela, J. Y., J. M. DeRouchey, S. S. Dritz, M. D. Tokach, R. D. Goodband, J. L. Nelssen, R. C. Sulabo, R. C. Thaler, L. Brandts, D. E. Little, and K. J. Prusa. 2011. Amino acid digestibility and energy content of deoiled (solvent-extracted) corn distillers dried grains with solubles for swine and effects on growth performance and carcass characteristics. Journal of animal science 89, 1817-1829.

Jones, C. K., J. R. Bergstron, M. D. Tokach, J. M. DeRouchey, R. D. Goodband, J. L.

Nelssen, and S. S. Dritz. 2010. Efficacy of commercial enzymes in diets containing various concentrations and sources of dried distiller's grains with solubles for nursery pigs. Journal of Animal Science 88, 2084-2091.
Kessler. 2017. The impact of feeding growing-finishing pigs with reduced dietary protein levels on performance, carcass traits, meat quality and environmental impacts. Livestock Science 198, 162-169.National Swine Nutrition Guide, 2010. US Pork Center of Excellence (USPCE); https://www.usporkcenter.org/product/national-swine-nutrition-guide/
Klasing, K. C. 2012. Displacement Values for US Corn DDGS—Informed by Regionally Specific Least-Cost Diet Formulation for All Major Livestock Types. International Council on Clean Transportation. Working Paper no. 2012-3.
Lei, X. G., J. D. Weaver, E. Mullaney, A. H. Ullah, and M. J. Azain. 2013. Phytase a new life for an "old" enzyme. Annual Review of Animal Biosciences 1, 283-309.
Mackenzie, S.G., I. Leinonen, N. Ferguson, and I. Kyriazakis. 2016. Can the environmental impact of pig systems be reduced by utilizing co-products as feed? Journal of Cleaner Production. 115: 172-181.
Makkar, H. P. S. 2016. Animal nutrition in a 360-degree view and a framework for future R&D work: towards sustainable livestock production. Animal Production Science. http://dx.doi.org/10.1071/AN15265
Matlock, M. et al., 2014. A life cycle analysis of water use in U.S. pork production - Comprehensive Report, s.l.: University of Arkansas & Pork Checkoff.
Monteiro, A. N. T. R., T. M. Bertol, P. A. V. Oliveira, J. Y. Dourmad, A. Cobella, and A. M.
National Research Council (NRC). 2012. Nutrient Requirements of Swine. 11th ed. National Academy Press, Washington, D.C.
National Swine Nutrition Guide (NSNG). 2010. National swine nutrition guide tables on nutrient recommendations, ingredient composition, and use rates. U.S. Pork Center of Excellence, USA.
Ogino, A., T. Osada, R. Takada, T. Takagi, S. Tsujimoto, T. Tonoue, D. Matsui, M. Katsumata, T. Yamashita and Y. Tanaka. 2013. Life cycle assessment of Japanese pig farming using low-protein diet supplemented with amino acids. Soil Science and Plant Nutrition 59, 107-118.
Pelton, R. E. O. 2016. Improving sustainability management decisions with modified life cycle assessment methods. Ph.D. diss., University of Minnesota.
Pomar, C., Dubeau, F., Létourneau-Montminy, M.-P., Boucher, C., & Julien, P.-O. (2007). Reducing phosphorus concentration in pig diets by adding an environmental objective to the traditional feed formulation algorithm. Livestock Science, 111(1), 16–27. https://doi.org/10.1016/j.livsci.2006.11.011
Salim, H. M., Z. A. Kruk, and B. D. Lee. 2010. Nutritive value of corn distillers dried grains with solubles as an ingredient of poultry diets: A review. World's Poultry Science Journal 66, 411-432.
Shepon, A., Eshel, G., Noor, E., & Milo, R. (2016). Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. under review. Environmental Research Letters, 11(10), 1–8. https://doi.org/10.1088/1748-9326/11/10/105002
Shurson, J.; Alghamdi, A. S. (2008). Quality and New Technologies To Create Corn Co-Products From Ethanol Production. Using Distillers Grains in the U.S. and International Livestock and Poultry Industries: The Current State of Knowledge. CARD, Iowa State University, Ames. IA., 231–259.
Simons, P. C. M., H. A. J. Versteeg, A. W. Jongbloed, P. A. Kemme, P. Slump, K. D. Bos, M. G. E. Wolters, R. F. Beudeker, and G. J. Verschoor. 1990. Improvement of phosphorus

availability by microbial phytase in broilers and pigs. British Journal of Nutrition 64, 525-540.
Smith T, Goodkind A, Kim T, Pelton R, Suh K, Schmitt J (2017). Subnational mobility of U.S. corn: implications for consumption based environmental accounting. Proc Natl Acad Sci USA 114(38):E7891-E7899
Stein, H. H., and G. C. Shurson. 2009. Board-invited review: The use and application of distillers dried grains with solubles in swine diets. Journal of animal science 87, 1292-1303.
Thoma, G. et al., 2011. National life cycle carbon footprint study for production of US swine., s.l.: United States National Pork Board.
van Holsteijn, F. H., M. de Vries, and H.P.S Makkar. Identification of Indicators for Evaluating Sustainability of Animal Diets. FAO Animal Production and Health Working Paper. No. 15. Rome, Italy.
Veum, T. L., D. W. Bollinger, C. E. Buff, and M. R. Bedford. 2006. A genetically engineered Escherichia coli phytase improves nutrient utilization, growth performance, and bone strength of young swine fed diets deficient in available phosphorus. Journal of Animal Science 84,1147-1156.
Wang J et al (2012) China's water-energy nexus: greenhouse-gas emissions from groundwater use for agriculture. Environ Res Lett 7(1):1–10
Wu, F., L. J. Johnston, P. E. Urriola, A. M. Hilbrands, and G. C. Shurson. 2016. Evaluation of NE predictions and the impact of feeding maize distillers dried grains with solubles (DDGS) with variable NE content on growth performance and carcass characteristics of growing-finishing pigs. Animal Feed Science and Technology 215, 105-116.
Zeng, Z. K., G. C. Shurson, and P. E. Urriola. 2017. Prediction of the concentration of standardized ileal digestible amino acids and safety margins among sources of distillers dried grains with solubles for growing pigs: A meta-analysis approach. Animal Feed Science and Technology 231, 150-159.
Zijlstra, R. T., & Beltranena, E. (2013). Swine convert co-products from food and biofuel industries into animal protein for food. Animal Frontiers, 3(2), 48–53. https://doi.org/10.2527/af.2013-0014
United Nations. (2015). The Millennium Development Goals Report. New York.
USDA NASS. 2018. Quarterly Hogs and Pigs. United States Department of Agriculture. Economics Statistics and Market Information System. Washington, D.C. http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1086.

Appendix A – Feed Formulations

Table 8: Overall ingredient and nutritional composition of the growing-finishing pig diet in Mid-West region. All ingredient inclusions shown in g/kg as fed, all calculated value shown as percent as fed.

Item	Control	DDGS	Food waste	Synthetic AA	Inorganic P

Corn	747.70	478.08	506.00	943.83	734.00
DDGS	0.00	275.00	0.00	0.00	0.00
Food waste	0.00	0.00	87.50	0.00	0.00
SBM, 46.5%	219.38	218.80	223.95	0.00	237.88
Wheat middlings	0.00	2.23	164.53	13.18	0.00
Choice White Grease	4.83	3.50	1.13	0.80	3.60
Limestone	7.70	11.13	8.10	8.65	12.08
Monocalcium phosphate	10.68	3.98	1.70	12.00	2.45
Salt	3.13	3.13	3.13	3.13	3.13
Vitamin mineral mix	3.00	3.00	3.00	3.00	3.00
L-lysine-HCl	1.90	0.93	0.28	8.68	1.38
L-Tryptophan	0.08	0.00	0.00	1.10	0.03
L-Threonine	1.20	0.25	0.58	4.15	1.13
DL-Methionine	0.48	0.00	0.13	1.50	0.45
Choline chloride, 50%	0.00	0.00	0.00	0.00	0.00
Phytase	0.00	0.00	0.00	0.00	0.90
Total	1000.00	1000.00	1000.00	1000.00	1000.00
Calculated value					
ME, Kcal/kg	3377.78	3377.78	3377.78	3377.78	3377.78
Crude Protein, %	16.85	21.85	19.95	9.35	17.40
Standardized Ileal Digestibility Amino Acid ratio					
Lys / Lys	0.88	0.88	0.89	0.88	0.89
Thr / Lys	0.64	0.67	0.66	0.64	0.66
Met / Lys	0.29	0.34	0.31	0.30	0.30
Trp / Lys	0.17	0.19	0.20	0.16	0.17
Crude fat, %	4.08	5.63	4.85	3.80	3.90
Crude fiber, %	2.65	3.45	3.45	2.28	2.73
Total Ca, %	0.62	0.61	0.61	0.61	0.61
Total P, %	0.57	0.55	0.58	0.50	0.42
Available P, %	0.26	0.28	0.32	0.27	0.25
STTD P, %	0.26	0.26	0.33	0.26	0.28

Table 9: Overall ingredient and nutritional composition of the growing-finishing pig diet in Mid-Atlantic region. All ingredient inclusions shown in g/kg as fed, all calculated value shown as % as fed.

Item	**Control**	**DDGS**	**Food waste**	**Synthetic AA**	**Inorganic P**
Corn	780.45	431.25	571.48	907.90	674.53
DDGS	0.00	275.00	0.00	0.00	0.00
Food waste	0.00	0.00	87.50	0.00	0.00
SBM, 46.5%	181.30	140.93	163.73	0.00	248.78
Wheat middlings	0.00	114.35	154.88	41.38	45.60
Choice White Grease	5.65	12.28	0.40	5.83	7.65
Limestone	8.00	11.53	7.28	8.70	11.88
Monocalcium phosphate	12.85	4.80	5.05	14.98	2.63
Salt	3.13	3.13	3.13	3.13	3.13
Vitamin mineral mix	3.00	3.00	3.00	3.00	3.00
L-lysine-HCl	3.08	2.93	2.08	8.50	0.88
L-Tryptophan	0.18	0.00	0.00	1.08	0.00
L-Threonine	1.73	0.83	1.18	4.05	0.70
DL-Methionine	0.65	0.00	0.30	1.48	0.35
Choline chloride, 50%	0.00	0.00	0.00	0.00	0.00
Phytase	0.00	0.00	0.00	0.00	0.90
Total	1000.00	1000.00	1000.00	1000.00	1000.00
Calculated value					
ME, Kcal/kg	3344.00	3352.45	3344.00	3344.00	3344.00
Crude Protein, %	15.18	19.83	17.85	9.48	18.05
Standardized Ileal Digestibility Amino Acid ratio					
Lys / Lys	0.88	0.88	0.88	0.88	0.88
Thr / Lys	0.64	0.64	0.64	0.64	0.64
Met / Lys	0.29	0.31	0.29	0.30	0.29
Trp / Lys	0.16	0.16	0.16	0.16	0.17
Crude fat, %	4.15	6.45	4.80	4.30	4.33
Crude fiber, %	2.60	4.60	3.25	2.43	3.00
Total Ca, %	0.61	0.61	0.61	0.62	0.61
Total P, %	0.61	0.61	0.63	0.61	0.45
Available P, %	0.33	0.33	0.38	0.37	0.26
STTD P, %	0.32	0.31	0.39	0.35	0.30

Table 10: Overall ingredient and nutritional composition of the growing-finishing pig diet in Central region. All ingredient inclusions shown in g/kg as fed, all calculated value shown as % as fed.

Item	**Control**	**DDGS**	**Food waste**	**Synthetic AA**	**Inorganic P**
Corn	695.28	446.18	543.23	893.53	673.30
DDGS	0.00	275.00	0.00	0.00	0.00
Food waste	0.00	0.00	87.50	0.00	0.00
SBM, 46.5%	186.80	136.58	177.28	0.00	221.35
Wheat middlings	76.15	104.20	167.38	55.63	71.40
Choice White Grease	11.30	11.45	2.18	6.65	9.15
Limestone	8.85	11.38	8.30	8.60	11.95
Monocalcium phosphate	10.58	5.10	4.70	14.50	2.83
Salt	3.13	3.13	3.13	3.13	3.13
Vitamin mineral mix	3.00	3.00	3.00	3.00	3.00
L-lysine-HCl	2.68	3.08	2.10	8.55	1.58
L-Tryptophan	0.10	0.05	0.00	0.95	0.00
L-Threonine	1.50	0.88	0.95	4.08	1.03
DL-Methionine	0.65	0.00	0.28	1.40	0.40
Choline chloride, 50%	0.00	0.00	0.00	0.00	0.00
Phytase	0.00	0.00	0.00	0.00	0.90
Total	1000.00	1000.00	1000.00	1000.00	1000.00
Calculated value					
ME, Kcal/kg	3344.00	3352.45	3344.00	3344.00	3344.00
Crude Protein, %	16.08	19.60	17.80	9.48	17.25
Standardized Ileal Digestibility Amino Acid ratio					
Lys / Lys	0.88	0.88	0.92	0.88	0.88
Thr / Lys	0.64	0.64	0.64	0.64	0.64
Met / Lys	0.30	0.30	0.30	0.30	0.29
Trp / Lys	0.16	0.16	0.17	0.16	0.17
Crude fat, %	4.73	6.55	4.95	4.30	4.50
Crude fiber, %	3.03	4.63	3.33	2.43	3.08
Total Ca, %	0.61	0.61	0.65	0.62	0.61
Total P, %	0.61	0.61	0.63	0.61	0.46
Available P, %	0.31	0.32	0.38	0.37	0.26
STTD P, %	0.31	0.31	0.39	0.35	0.29

Table 11: Overall ingredient intake of growing-finishing pig diet in Mid-West region (Unit: kilogram)

Item	Control	DDGS	Food waste	Synthetic AA	Inorganic P
Corn	190.20	120.85	127.78	238.92	186.65
DDGS	-	70.75	-	-	-
Food waste	-	-	22.71	-	-
SBM, 46.5%	54.84	54.67	55.23	-	59.63
Wheat middlings	-	0.60	43.11	3.61	-
Choice White Grease	1.16	0.82	0.23	0.17	0.85
Limestone	1.96	2.83	2.03	2.19	3.06
Monocalcium phosphate	2.63	0.91	0.36	2.96	0.56
Salt	0.79	0.79	0.79	0.79	0.79
Vitamin mineral mix	0.76	0.76	0.76	0.76	0.76
L-lysine-HCl	0.46	0.20	0.06	2.15	0.32
L-Tryptophan	0.02	-	-	0.28	0.01
L-Threonine	0.32	0.07	0.16	1.05	0.29
DL-Methionine	0.13	-	0.03	0.38	0.12
Phytase	-	-	-	-	0.23
Total	253.25	253.25	253.25	253.25	253.25

Table 12: Overall ingredient intake of growing-finishing pig diet in Mid-Atlantic region (Unit: kilogram)

Item	Control	DDGS	Food waste	Synthetic AA	Inorganic P
Corn	198.84	107.50	143.25	230.08	171.39
DDGS	-	70.75	-	-	-
Food waste	-	-	22.71	-	-
SBM, 46.5%	44.85	35.02	40.41	-	62.33
Wheat middlings	-	30.36	41.37	10.52	11.79
Choice White Grease	1.36	3.14	0.08	1.42	1.90
Limestone	2.02	2.94	1.84	2.20	3.00
Monocalcium phosphate	3.20	1.08	1.14	3.71	0.61
Salt	0.79	0.79	0.79	0.79	0.79
Vitamin mineral mix	0.76	0.76	0.76	0.76	0.76
L-lysine-HCl	0.76	0.70	0.49	2.11	0.19
L-Tryptophan	0.05	-	-	0.27	-
L-Threonine	0.46	0.21	0.31	1.03	0.19
DL-Methionine	0.17	-	0.08	0.37	0.09
Phytase	-	-	-	-	0.23
Total	253.25	253.25	253.25	253.25	253.25

Table 13: Overall ingredient intake of growing-finishing pig diet in Central region (Unit: kilogram)

Item	**Control**	**DDGS**	**Food waste**	**Synthetic AA**	**Inorganic P**
Corn	176.79	112.28	136.15	226.40	170.70
DDGS	-	70.75	-	-	-
Food waste	-	-	22.71	-	-
SBM, 46.5%	46.27	34.46	45.13	-	55.67
Wheat middlings	19.73	26.35	43.33	14.17	18.41
Choice White Grease	2.82	2.83	0.46	1.63	2.28
Limestone	2.24	2.88	2.08	2.17	3.01
Monocalcium phosphate	2.61	1.19	1.07	3.59	0.66
Salt	0.79	0.79	0.79	0.79	0.79
Vitamin mineral mix	0.76	0.76	0.76	0.76	0.76
L-lysine-HCl	0.66	0.73	0.47	2.12	0.36
L-Tryptophan	0.03	0.01	-	0.24	-
L-Threonine	0.40	0.22	0.24	1.04	0.27
DL-Methionine	0.17	-	0.07	0.36	0.11
Phytase	-	-	-	-	-
Total	253.25	253.25	253.25	253.25	253.25

Appendix B – Total environmental impacts

Table 14: Water use of pig diets from corn feed inputs, including corn farming and DDGS, by region (m^3)

Region	Control	DDGS	Food Waste	Synthetic AA	Inorganic P
Mid-West	704,401,693	693,917,275	482,665,343	899,270,416	681,476,750
Mid-Atlantic	45,495,851	50,846,396	34,872,856	67,683,917	38,428,926
Central	572,582,824	556,477,793	517,520,639	964,739,164	653,341,847
Total US	1,322,480,368	1,301,241,464	1,035,058,838	1,931,693,497	1,373,247,523

Table 15: Land use of pig diets from corn feed inputs, including corn farming and DDGS, by region (acres)

Region	Control	DDGS	Food waste	Synthetic AA	Inorganic P
Mid-West	5,719,027	6,231,024	3,882,592	7,175,525	5,688,109
Mid-Atlantic	1,336,605	1,458,505	938,619	1,552,060	1,130,154
Central	485,590	515,992	357,726	587,104	463,978
Total US	7,541,222	8,205,521	5,178,937	9,314,689	7,282,241

Table 16: GHG emissions of pig diets from corn feed inputs, including corn farming and DDGS, by region (kgCO2e)

Region	Control	DDGS	Food Waste	Synthetic AA	Inorganic P
Mid-West	6,406,891,176	6,970,381,603	4,346,135,878	8,060,822,173	6,381,876,886
Mid-Atlantic	1,479,865,396	1,726,466,135	1,041,389,699	1,715,291,099	1,246,735,505
Central	611,518,816	635,349,477	466,381,166	784,046,433	613,622,846
Total US	8,498,275,388	9,332,197,215	5,853,906,743	10,560,159,705	8,242,235,237

Table 17: Total GHG emissions from pig diets by region (kgCO2e)

Region	Control	DDGS	Food Waste	Synthetic AA	Inorganic P
Mid-West	15,810,938,838	18,806,003,144	16,158,919,168	17,967,307,870	15,834,210,425
Mid-Atlantic	4,932,138,797	8,464,557,477	5,655,998,547	5,256,125,397	5,090,850,806
Central	2,012,479,740	2,406,114,004	2,136,968,988	2,033,703,847	2,031,478,660
Total US	22,755,557,375	29,676,674,625	23,951,886,704	25,257,137,114	22,956,539,891

Appendix C – Total environmental impacts with an economic allocation of environmental impacts for DDGS

Table 18: Per pig water use from corn feed inputs, including corn farming and DDGS, by region (m^3/pig) for 19.9% economic allocation to DDGS

Region	Control	DDGS	Food Waste	Synthetic AA	Inorganic P
Mid-West	8.21	**6.75**	5.62	10.48	7.94
Mid-Atlantic	2.25	**1.97**	1.73	3.35	1.90
Central	69.78	**62.33**	63.07	117.58	79.63
Total US	11.58	**9.89**	9.06	16.91	12.02

Table 19: Per pig land use from corn feed inputs, including corn farming and DDGS, by region (acres/1,000 pigs*) for 19.9% economic allocation to DDGS

Region	Control	DDGS	Food waste	Synthetic AA	Inorganic P
Mid-West	66.65	**57.63**	45.25	83.62	66.29
Mid-Atlantic	66.15	**54.28**	46.46	76.82	55.94
Central	59.18	**49.31**	43.60	71.55	56.55
Total US	66.02	**56.44**	45.34	81.55	63.76

*Note the units here are different from other tables in order to show the variation across regions and diets.

Table 20: Per pig GHG intensity from pig diets by region (kgCO2e/pig) for 19.9% economic allocation to DDGS

Region	Control	DDGS	Food Waste	Synthetic AA	Inorganic P
Mid-West	184.3	**202.2**	188.3	209.4	184.5
Mid-Atlantic	244.1	**396.3**	279.9	260.1	252.0
Central	245.3	**278.3**	260.4	247.9	247.6
Total US	199.2	**242.2**	209.7	221.1	201.0