7-7-2018

A Retrospective Assessment of US Pork Productions: 1960 to 2015

Ben Putman

Jacob Hickman

Prathamesh Bandekar

Marty Matlock
mmatlock@uark.edu

Greg Thoma

Recommended Citation
Putman, B., Hickman, J., Bandekar, P., Matlock, M., & Thoma, G. (2018). A Retrospective Assessment of US Pork Productions: 1960 to 2015. *University of Arkansas Resiliency Center.* Retrieved from https://scholarworks.uark.edu/rescentfs/2

A Retrospective Assessment of US Pork Production: 1960 to 2015

Final Report

Ben Putman, M. S.

Jacob Hickman

Prathamesh Bandekar, M. S.

Marty Matlock, PhD., P. E.

Greg Thoma, Ph.D., P.E.

July 7, 2018

Executive Summary

1 Introduction

The primary goal of this study is to assess the carbon, energy, water and land footprints per kg (2.2 pounds) of live weight (LW) pork produced at five-year increments between 1960 and 2015. This assessment utilizes the Life Cycle Assessment (LCA) methodology, which is a technique to assess the potential environmental impacts associated with a product system by compiling an inventory of relevant energy and material flows, evaluating the associated burdens, and interpreting the results to assist in making more informed decisions and to provide an understanding of the drivers of change over the past 55 years. This LCA is “cradle-to-farm gate” e.g. covering the material and energy flows associated with the full supply chain beginning with extraction of raw materials through the production of live, market-weight swine, inclusive of culled sows, at the farm gate. On average, production-weighted metrics declined across all four categories over the assessment period. The largest decrease was seen in land use (75.9 percent), followed by water use (25.1 percent), then global warming potential (7.7 percent), and finally energy use (7.0 percent).

2 Methods

The life cycle inventory (LCI) data for this assessment were established using a variety of sources including peer-reviewed literature, industry reports, government databases, and the Pork Production Environmental Footprint Calculator (PPEFC). These sources informed the calculation of LCI values through a multi-step modeling process in which literature references supported the creation of live swine production simulations in the PPEFC. These simulations were created to represent typical swine farms, during each of the five-year increments of the study, in the PPEFC. The outputs from the PPEFC were then imported to SimaPro software to conduct the impact assessment portion of this LCA. A database was created across all production states and counties included in the evaluation to store demographic production data in the five-year increments necessary for the assessment.

2.1 Standard Swine Farms

Three categories of data were required to build the standard types of swine farms in the PPEFC: production locations (to determine the weather), animal characteristics, and production facility characteristics. These data were used to generate input farm files for the PPEFC. Each farm file included both sow barns and grow-finish barns, the number of each barn type was determined by the year and county simulated, based on the USDA report of market and breeding inventory. Sow barns simulated gestation and lactation phases and produced weaned piglets and culled sows. Grow-finish barns simulated pig growth and performance from weaning to market weight.

2.1.1 Production locations

States included in this study were selected based on their total hog inventories from 1960 to 2015. The cumulative production of the states selected for simulations represented 90 percent of national swine production during each year of the study period. Once the list of states for the study period was determined, a subset of counties from each state were selected based on their total inventory in each of the simulation years. Counties were included in the analysis if they had the largest total inventory, for that state, in any given simulation year throughout the assessment period. Thus, a county selected for any of the simulation years remained in the list of counties for all simulation years unless the inventory in that county dropped to zero. After discussion with industry experts, several more counties were added to create a more robust geographic representation in states where the top counties were isolated to one area of that state. The final list of states and the number of counties used for simulations in each are presented in Table ES 1.

2.1.2 Animal characteristics

Grow-finish barns in each simulation year assumed incoming piglets weighed approximately 13 lbs. In 1960, hogs were finished at 200 lbs.; Finishing weights increased steadily over the assessment period and reached 282 lbs. in 2015. As finishing weights increased, feed conversion ratio (FCR) also improved. In 1960, the average FCR was estimated to be 4.5 lbs. of feed per pound of LW produced. By 2015, the FCR had improved to 2.8. Mortality rates in the grow-finish barn were simulated to be approximately 2 percent for a majority of the assessment period due to a lack of historical data. In recent

Table ES 1. A list of the states considered for this assessment and the subsequent number of counties within each state that were simulated.

State	Counties	State	Counties	State	Counties
Alabama	6	Kentucky	4	Oklahoma	3
Arkansas	4	Michigan	2	Pennsylvania	1
Colorado	4	Minnesota	5	South Carolina	6
Georgia	5	Mississippi	3	South Dakota	3
Illinois	13	Missouri	7	Tennessee	3
Indiana	1	Nebraska	4	Texas	4
Iowa	8	North Carolina	2	Virginia	3
Kansas	4	Ohio	3	Wisconsin	1

years, data suggest an increase in the mortality rate, which peaks at 8.3 percent in 2015, likely associated with PEDV. Key performance characteristics simulated in the grow-finish barns are presented in Table ES 2.

The piglets produced per sow and the number of piglets that survived to weaning increased over the assessment period. In 1960, sows were simulated as having 10 piglets per litter with seven surviving to weaning. By 2015, those numbers increased to 13.5 and 10, respectively. We assumed that the replacement rate of sows in the sow barns remained relatively constant over the assessment period at 50 percent annually; however, the mortality rate for sows varied throughout the years. The performance characteristics simulated in the sow barns are presented in Table ES 2.

2.1.3 Production facilities

The PPEFC was not designed to model extensive, pasture-based, systems that were common farming practice in the 1960s, thus, to construct representative simulations for the reference years 1960, 1965, and 1970, we simulated grow-finish and sow barns using the "hoop barn" designation. We set hoop barn parameters to exclude fans and lights, piglet cooling equipment, and set the R-value of the walls and ceiling to 0. The only energy use for these systems was associated with piglet heaters in the sow barn. By 1975, hog farming was becoming more technologically advanced, and the number of pigs produced per farm increased as more permanent pig production facilities were constructed. The growth in swine farms during the 1970s occurred primarily in the Southeast, as hog farming spread outside of the Corn Belt.

Table ES 2. National average performance characteristics simulated in Grow-finish and Sow barns for each reference year.

Year	**Grow –finish mortality (% pigs)**	**FCR**	**ADG (lbs./day)**	**Market weight (kg)**	**Days on feed**	**Piglets per litter**	**Weaned piglets per litter**	**Sow barn mortality (% annual)**
1960	1.8%	4.5	1.6	90.7	124.5	10.0	7.0	3.0%
1965	1.7%	4.6	1.6	95.3	134.2	10.1	7.2	3.0%
1970	1.7%	4.7	1.3	99.8	163.4	9.8	7.3	3.0%
1975	1.4%	4.7	1.4	105.2	162.9	9.2	7.3	3.0%
1980	1.4%	3.9	1.5	103.0	148.3	10.4	7.5	6.0%
1985	1.7%	4.1	1.5	103.0	155.3	9.2	7.3	6.0%
1990	2.0%	4.4	1.4	112.9	178.3	10.3	8.4	6.0%
1995	2.1%	3.5	1.8	116.1	142.5	10.0	8.5	9.0%**
2000	2.7%	3.2	1.8	118.8	146.2	10.8	8.8	12.0%**
2005	1.7%	3.0	1.7	122.0	162.4	11.8	9.4	1.0%**
2010	4.3%	2.8	1.6	121.9	168.3	13.0	10.0	3.0%
2015	1.7%	2.8	1.6	127.6	172.9	13.5	10.0	3.0%

** the fluctuations in sow mortality are primarily the result of changes in the reporting categories. The simulations in each year assumed a 50% replacement rate for sows (death + marketed). This variability falls below the 1% threshold requiring higher resolution data.

These newer operations were markedly different than their Midwestern counterparts, making use of solid walled construction, and mechanized cooling, which were reflected in the Southern county simulations. These types of production facilities make up a greater portion of the farm simulations over the course of the assessment period, reaching 100 percent confinement in 1990.

Figure ES 1 shows the evolution of manure management systems with significant use of solid storage until about 1980 when anaerobic lagoons and deep-pit systems become more widespread. Regarding the emissions associated with manure management, in this analysis we have included the emissions from field application of manure after the on-farm treatment or storage stage. This accounting ensures a consistent system boundary across the entire temporal series.

2.2 Rations

Feed rations for the PPEFC were based on recommended rations and the individual ingredients' nutritional values published by the National Research Council (NRC) in the Nutrient Requirements of Swine publications. The initial ration formulation and list of ingredients was adopted from the 2nd edition (1973) as it was earliest edition available. That initial formulation was used in the simulations for 1960 through 1975, and for subsequent years, the edition published closest to the reference year was used. Feed

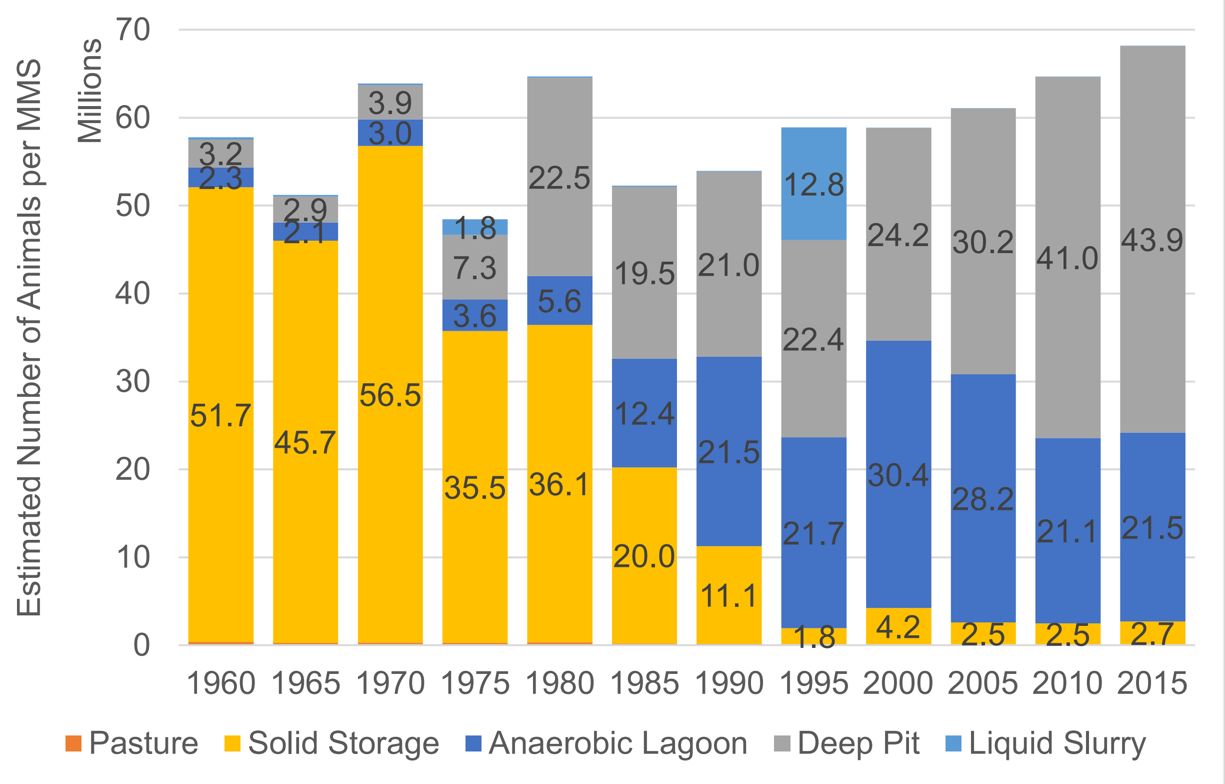

Figure ES 1. Distribution of hogs among manure management systems. State-level data regarding number and type of manure management was used in simulations. Here is inventory-weighted distribution of manure management at national level.

rations were formulated using the NRC nutrient requirements and an initial set of ingredients, which primarily consisted of corn, soybean meal, minerals, and vitamins (Table ES 3). For sow barn rations, we formulated two distinct rations: for gestating sows and for lactating sows. For grow-finish barn rations, we formulated multiphase rations that followed the number of phases given in the NRC publication of reference to reach the market weight of each simulation year. While swine diets have become more homogenous over time, corn and soybean-based diets have been commonly fed to pigs since 1960. As such, those two commodities were selected as the primary ration constituents for the entire assessment timeframe; however, the list of included ingredients was expanded during the later-year simulations to include distiller's grains. Using information available in the literature and consultation with industry experts, the list of ingredients for rations was expanded according to common practice at the time.

Table ES 3 presents the ration ingredients and the year of their inclusion in the simulated rations. Except for the inclusion of dried distillers' grains (DDGS) into diets, we did not formulate rations with different ingredients within the same reference year and for the same barn type. That is to say, all grow-finish barns in any given year, regardless of location, used the same ration. A spreadsheet-based least-cost

Table ES 3. A list of the changes made to the base ration over the assessment period and the simulation year in which those changes were implemented.

Simulation year	Description
1960	Base ration formulated using guidelines from NRC (NRC 1973). Includes corn, soybean meal, dicalcium phosphate, limestone, salt, vitamin/mineral mix
1970	Addition of poultry fat and two crystalline amino acids (Lysine and Methionine)
1980	Rations reformulated using updated nutrient recommendations (NRC 1979)
1985	Addition of two more crystalline amino acids (Tryptophan and Threonine)
1990	Rations reformulated using updated nutrient recommendations (NRC 1988)
1995	Soybean meal changed to de-hulled, moving from 44 percent to 48 percent crude protein
2000	Addition of Ractopamine into grow-finish barn rations, updated nutrient requirements (NRC 1998)
2005	Addition of DDGS
2010	Addition of crystalline amino acid Valine and updated nutrient requirements (NRC 2012)

ration formulation tool known as WUFFDA[1] was used to formulate each ration based on nutrient requirements and allowable ingredient inclusion rates for each of the grow-finish and sow barn rations in a given simulation year. Nutrient requirements for each phase were entered into the WUFFDA calculator along with the list of available ingredients. Each available ingredient was assigned a set of parameters which described its nutrient contents, its minimum and maximum inclusion rates for each phase, and its price. The WUFFDA calculator performs a least cost ration formulation subject to the constraints above.

We used the nutrient profiles of each ingredient from the same NRC publication which informed the swine nutrient requirements for that simulation year. The price data was primarily informed by data from the USDA Economic Research Service. In the event that data were not available for the entire time period of this assessment, prices were linearly interpolated to fill in the price data for missing years.

2.3 Feeds

In general, there were three classes of feeds that required time-dependent models: crops, poultry by-products, and non-agriculture feeds. The methodological guidelines we followed in creating production models for each of the simulation years are outlined in the following sections.

2.3.1 Crops

Life cycle inventory (LCI) data for crop production were collected from each of the top five corn and soybean producing states in the United States. Illinois, Indiana, Iowa, Minnesota, and Nebraska were the top five throughout the assessment period, and collectively they produced 59 to 68 percent and 47 to 61 percent of all U.S. corn and soybeans, respectively. USDA census and survey data from these states were used to determine LCI data for yield, irrigation water, fertilizers, and pesticides. Emissions associated with nitrogen fertilizer applications and crop residues were calculated using IPCC methods. Fuel use associated with planting, irrigating, and harvesting was estimated using crop budgets published by extension services in each of the five states. Since historic crop budgets were not available, fuel use was adjusted for each simulation year according data from tractor efficiency tests published by the Nebraska Tractor Test Lab. Data from all five states were used to create production-weighted LCI models for corn and soybean cultivation, representing national production during each simulation period.

2.3.2 Non-agricultural feedstuffs

Non-agricultural feeds like vitamins and minerals were represented by unit processes from the U.S. Ecoinvent database (USEI) v2.2. We assumed impacts associated with the production of these items

---

[1] https://goo.gl/So7nqn

remained constant over the assessment period. While this is likely to underestimate their contribution to potential impacts, particularly in the earlier simulation years, it is unlikely to undermine the robustness of conclusions drawn from the results of this assessment as these items are consumed in such small quantities and do not contribute significantly to environmental impacts associated with pork production.

2.4 Background systems

The USEI database was used to estimate the upstream impacts associated with background systems, i.e. energy, transportation, and raw material production. Many of the standard unit processes within the database were adapted to reflect the changes in efficiency over time. Using historical data, regression equations were developed and applied to unit processes such that the efficiency could be adjusted to represent each simulation year. For example, a report by the International Fertilizer Industry Association provided the energy efficiency of ammonia production plants from 1955 to 2008. The data in this report was used to derive a regression equation relating production efficiency to simulation year. This equation produced scaling factors for each simulation year, which were applied to the energy requirements within the USEI unit processes for nitrogen fertilizer production; thus, we have approximated the technology and efficiency gains in the supply chain over the timeframe of the study. Table ES 4 provides a list of all the types of processes that were adapted and the underlying sources of data. Production efficiencies of all other processes not listed in Table ES 4 were assumed to be constant over the assessment period; however, the composition of power generation sources for the electricity grid mix was altered to represent the historical mix of a given simulation year, based on available data from the United States Energy Information Agency. Line losses and other conversion efficiencies were assumed to be the constant across all simulations.

Table ES 4. The types of processes that were adapted to reflect changes in efficiency over the assessment period are presented alongside the total change in process efficiency from 1960 to 2015 and the data source used to calculate scaling factors.

Process	Efficiency change	Source
Tractor fuel use	31%	Nebraska Tractor Test Lab
General use motors	25%	Nebraska Tractor Test Lab
Nitrogen fertilizer production	33%	International Fertilizer Association
Road transport	18%	US Department of Energy
Rail transport	209%	US Department of Energy
Water transport	69%	US Department of Energy

3 Results and discussion

The state-average results are presented in Figure ES 2 based on one kg LW (market plus cull sow) at the farm gate in five-year intervals, starting in 1960 and ending in 2015. On average, production-weighted metrics declined across all four categories over the assessment period. The largest decrease was seen in land use (75.9 percent), followed by water use (25.1 percent), then GWP (7.7 percent), and finally energy use (7.0 percent).

The GWP results show a notable degree of variation from 1960 to 1970 due to the extensive nature of pig production during those years. Manure emissions from pigs raised in warmer, southern states were much higher than those in the northern states because nitrogen volatilization increases with temperature. This variability decreases in the 1970s and 1980s as production facilities become more advanced and manure storage moves indoors. This transition has the opposite effect on energy use, which had been reasonably consistent across states but is now more variable as fully enclosed production grows in southern states. The more modernized facilities initially increase energy use per kg LW with increased electricity and propane use for climate control, but over time these technologies improve pig performance and decrease impacts associated with production. As production in other regions follows suit, the variability once again declines as facilities throughout the United States are increasingly homogeneous.

The increase in GWP in 1970 is primarily driven by corn production, which experienced a drought year that drove yields down and water and energy use up because of increased irrigation. Water use per kg LW is predominantly driven by irrigation water used in feed production, ranging from 77 to 91 percent of water use, depending on the year. Irrigation water use in corn and soy production in the United States grew throughout the 1970s and combined with the expansion of heavily irrigated agriculture in Nebraska, water use per kg LW saw little improvement until 1985. Starting around this time, the GWP began a consistent decline throughout the next several decades, as production moved indoors, and facilities became more advanced, allowing for greater control over the production environment. With improvements in facilities came improved health and nutrition and as a result, impacts per kg LW declined during this time in all four impact categories.

Impacts continued to decline until 2005, which saw the introduction of DDGS into swine rations. The drying energy required to produce DDGS is associated with higher GHG emissions and energy use than the feeds that are replaced, causing a net increase in the GWP and energy use associated with pigs fed DDGS. Not all pig production takes place near ethanol facilities, which produce the distillers' grains as a byproduct, and therefore the variability in GWP and energy use increases in the 2000s as some rations include DDGS and others do not. Land use associated with pig production was approximately 99 percent from feed and this was consistent for production across the United States and throughout the assessment period. The steady decline in land use is representative of the improvement in corn and soybean yields in the country.

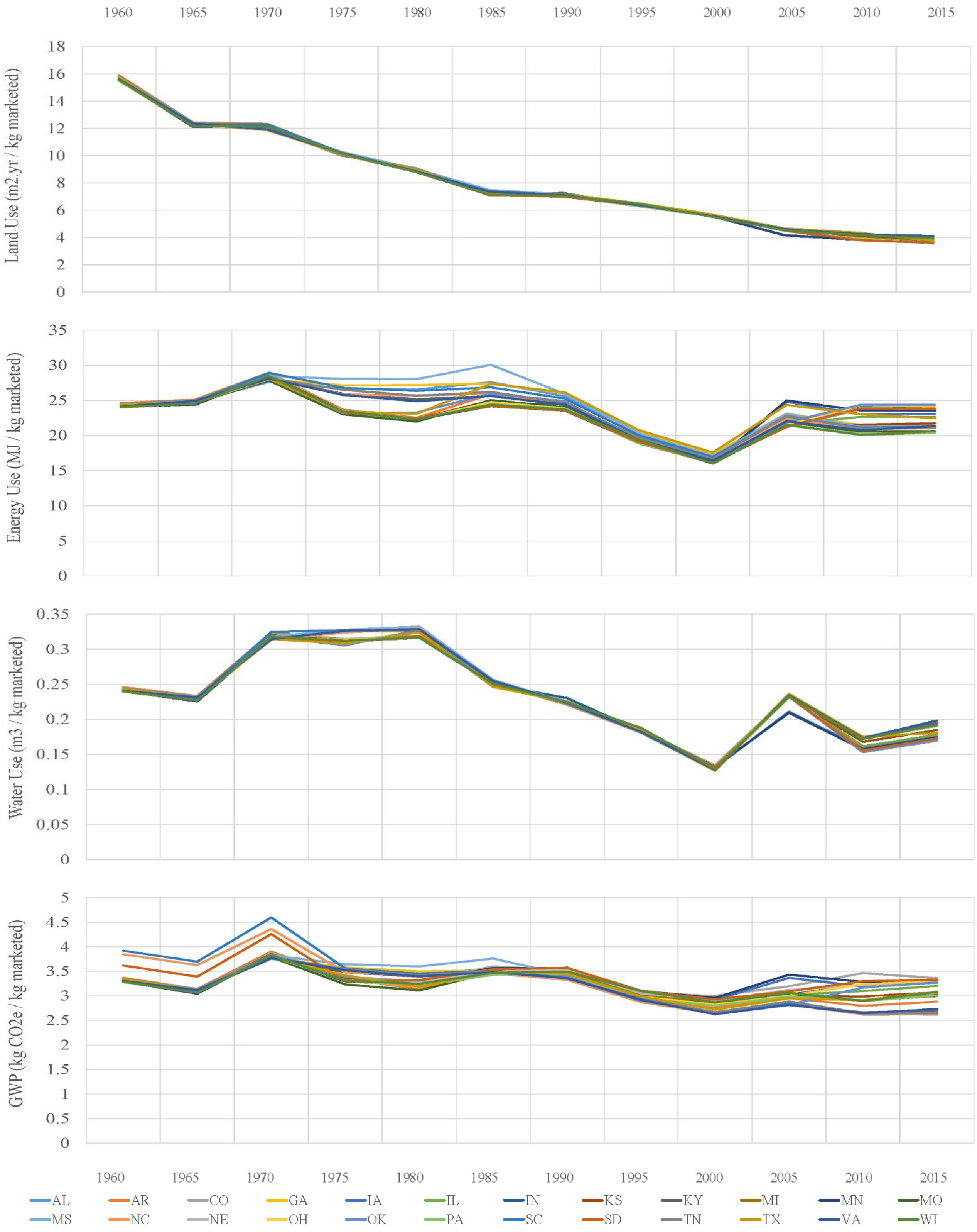

Figure ES 2. LCIA results are presented as the state production weighted (by county) average impact per kg LW (including cull sows) in each state from 1965 to 2015.

Annual pork production increased by 84 percent from 1960 to 2015. The impact intensity (per kg LW) associated with that production has steadily declined (Figure ES 2); however, because of the significant increase in production, three of the cumulative sector impacts have declined (GWP, energy and water), while land use generally decreased (Figure ES 3). The GWP, water use, and land use results track with sectoral output in production from 1960 to 1985. Cumulative water use breaks this trend in 1990 by declining slightly from 1985 despite an increase in production. By 1995, GWP and energy use also begin declining, despite further increases in annual production. This trend is reversed by 2005, which was the simulation year in which DDGS were added to the rations. The dramatic increase in water use in 2005 is coincidental to the addition of DDGS but is actually driven by higher water use in corn and soybean production. Despite producing nearly twice as much pork in 2015 as in 1960, the total land use associated with live animal production in the pork industry has continually declined. Steady gains in yield of corn and soybeans over this period were further amplified by the improvements in FCR of pigs. As a result, the pork supply chain occupies less than half of the land it did in 1960.

4 Conclusions

The United States swine industry has experienced many structural changes over the past 55 years. In addition, there have been continual improvements in the background supply chain supporting swine production. Within the industry, there has been a major shift from extensive to intensive production systems which initially increased environmental burden, but ultimately led to reductions through improved efficiencies: improved daily gain and feed conversion as well as increased fecundity and decreased mortality. There has also been a shift in the manure management practices, partially driven by the intensification of swine production over the period coupled with increased regulation. The environmental impacts per produced animal and kg LW have steadily declined since 1970 - 1980; however, because the total output of the sector has risen dramatically over the same period, there has been a slowly increasing cumulative environmental impact associated with entire sector driven by large growth of the sector output over the period. The sector level impact is estimated by weighted averaging of the simulated counties for each simulation year and aggregating to national production. **It is important to recognize that without the significant gains in reducing the footprint intensity of production that has occurred in the past 55 years, the cumulative environmental impacts for the whole sector would be much larger today.**

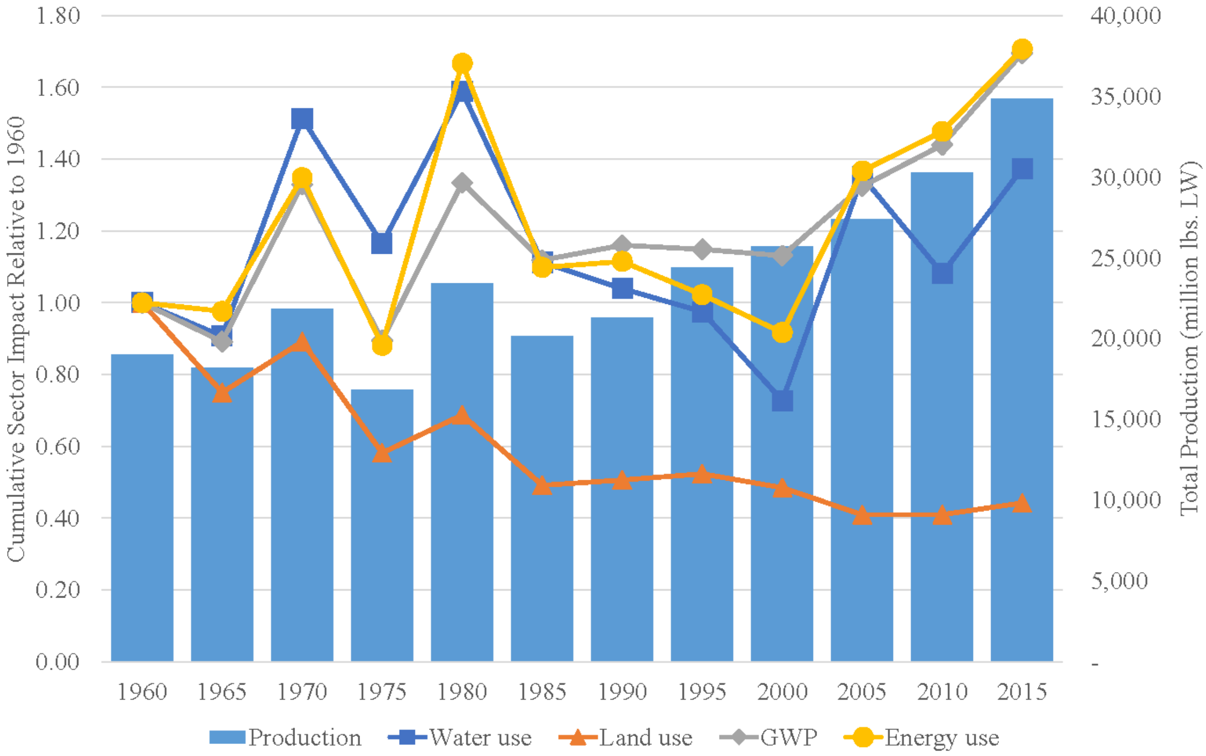

Figure ES 3. Annual pork production in the U.S. from 1960 to 2015 and the associated impacts. Pork production is shown in million pounds of LW pigs and is inclusive of market pigs and cull animals. Environmental impacts are presented in terms of the total industry impact to the farm gate relative to 1960 levels.

This page intentionally left blank.

Table of Contents

List of Figures

List of Tables

1 Introduction

The primary goal of this study is to assess the carbon, energy, water and land footprints per kg (2.2 pounds) of live weight (LW) pork, inclusive of culled sows, produced at five-year increments between 1960 and 2015. This assessment utilizes the Life Cycle Assessment (LCA) methodology, which is a technique to assess the potential environmental impacts associated with a product system by compiling an inventory of relevant energy and material flows, evaluating the associated burdens, and interpreting the results to assist in making more informed decisions and to provide an understanding of the drivers of change over the past 55 years. This LCA is "field-to-farm gate" e.g. covering the material and energy flows associated with the full supply chain beginning with extraction of raw materials through the production of live, market-weight swine, inclusive of culled sows, at the farm gate.

Overview of United States swine production: 1960 – 2015

In the 1960s there were over 640,000 farms selling hogs, most of which were small extensive operations. By the mid-1970s, there were 200,000 fewer farms selling hogs, but the number of hogs sold per farm had increased. From 1960 to 1974, farms that sold 1,000 head or more increased their share of the market from 7 to 25 percent. During this time, the largest pig producing states were in the Midwest, where an abundant supply of corn provided a cheap source of feed for the animals. In 1975, the Midwest region accounted for 78.6 percent of live weight produced. The Southwest and Southeast regions produced 2.4 percent and 14.8 percent, respectively. All other regions combined produced the remaining 4.2 percent.

With the 1980s came the first intensive hog operations. Facilities in Nebraska, Colorado, Oklahoma, and Kansas were built that had the capacity to produce 300,000 hogs per year. Production was also expanding into the Southeast, mainly in North Carolina. By 1986, North Carolina ranked seventh nationwide in pork production. Despite the increase in production beyond the Midwest, the total number of hog farms in the United States continued to decline as the production capacity per farm expanded.

By the mid-1990s, the total number of hog farms was still declining, reaching 150,000 in 1994. The United States swine industry was concentrated in a few states in the Midwest and North Carolina. From the mid-1980s to the mid-1990s, North Carolina moved from being the seventh to the second highest state for swine production. At about the same time, new regulations began to influence decisions regarding manure management practices (Nene et al., 2009). By the early 2000s, approximately 60 percent of the nation's hog inventory was concentrated in just four states: Iowa, North Carolina, Minnesota, and Illinois. During this period, hog inventories continued to increase in the Midwest, but began leveling off in North Carolina.

2 Methods

Life Cycle Assessment (LCA) is a technique to assess the potential environmental impacts associated with a product or process by compiling a field-to-farm-gate inventory of relevant energy and material inputs and environmental releases, evaluating the potential environmental impacts associated with identified inputs and releases, and interpreting the results in relation to farm management to assist in making more informed decisions. Broadly, an LCA consists of four stages (Figure 1):

1) Define the goal and scope – including appropriate metrics (e.g. greenhouse gas emissions, water consumption, hazardous materials generated, and/or quantity of waste);
2) Conduct life cycle inventories (collection of data that identifies the system inputs and outputs and discharges to the environment);
3) Perform impact assessment;
4) Analyze and interpret the results.

2.1 Goal and scope

The primary goal of this LCA is to perform an assessment of carbon, water and land footprints based on a per pound of pork produced basis at five-year increments between 1960 and 2015. The LCA is "field-to-farm gate" e.g. covering the material and energy flows associated with the production of raw materials through the production of live, market-weight swine at the farm gate. The primary audience for this LCA is the pork industry (growers, processors, packaging companies and retail) who may use the results to support internal decisions for increasing the efficiency, profitability, safety and security of the United States pork supply chain. Environmental impacts associated with production of infrastructure are not included in the analysis. Where data are incomplete, surrogate unit operations were identified for this

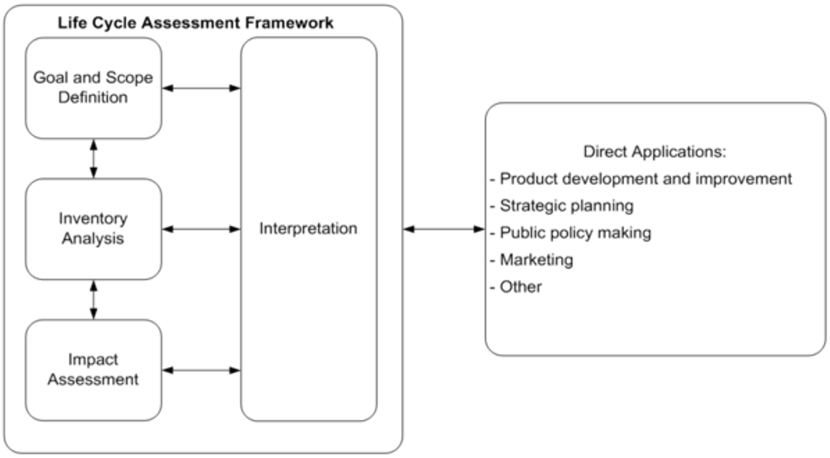

Figure 1. The stages of life cycle assessment.

analysis in the United States Ecoinvent v2.2 database (Frischknecht et al., 2005). In determining whether to expend additional effort to obtain specific inputs, cut-off criteria were established as a 1 percent contribution threshold for any impact category. Nonetheless, if data were readily available, the inputs were included despite being below the threshold.

2.1.1 System Boundary

For this assessment the system boundary was defined as "field-to-farm gate". This means that all inputs and emissions necessary to product 1 kg of live weight of marketed animals (finishers plus culled sows) are accounted in the assessment. The upstream boundary thus includes all extractions from nature necessary to product swine; as an example, coal mining and oil exploration are included in the upstream assessment of electricity and diesel fuel, respectively.

2.1.2 Functional Unit

For this study, the functional unit is 1 kg (2.2 lbs) live weight of marketed pig. This includes both finishers and cull sows. The computational structure of the lifecycle inventory model was designed to avoid the need for allocation between cull sows and piglets since the cull sows eventually join the finished animals at the harvesting stage. Because culled sows enter the food chain, we calculated impact metrics based on the combined marketed weight of cull sows and finished market hogs. Because each sow produces many market hogs, we added the estimated contribution of culled sows of approximately 6-7 kg of sow live weight per finished hog marketed to define the functional unit of 1 kg marketed LW. The amount varied depending on the year of simulation due to changing sow weights and number of live piglets weaned per litter.

2.2 Life cycle inventory

The life cycle inventory (LCI) data for this assessment were determined using a variety of sources including peer-reviewed literature, industry reports, government databases, and the Pork Production Environmental Footprint Calculator (PPEFC). These sources informed the calculation of LCI values through a multi-step modeling process in which literature references informed the creation of live swine production simulations. These simulations were created to represent typical swine farms in the PPEFC, the outputs from which were then imported to SimaPro to conduct the impact assessment portion of this LCA. The sources and methods used in the modeling process are defined in detail in the following sections.

2.2.1 Live swine production

The LCI data for pig production was produced using the PPEFC, which is a software tool that simulates the economic and environmental inputs and outputs associated with pork production.

Simulations in the PPEFC were structured such that each swine farm included a grow-finish barn and a sow barn. The sow barn encompassed the production of piglets from gestation and lactation of sows through weaning. Once piglets were weaned, they were transferred to the grow-finish barn where they were reared to market weight. It was assumed that incoming piglets were produced in sow barns within the same county. Input parameters for the PPEFC simulations were developed to represent national average production practices for each of the simulation years. When more detailed data were available, regional differences in production were incorporated. The derivation of these input parameters is described below.

2.2.1.1 National inventory

Each simulated farm in the PPEFC requires a county of production to be defined so that the appropriate weather files are incorporated. Creating a simulation file for each county that produced pigs throughout the United States across each of the twelve simulation years would be prohibitively time consuming; therefore, a set of locations were determined for use across all simulation years. In order to determine the simulation locations for the PPEFC, states analyzed during this study were selected based on their total hog inventories from 1960 to 2015 (Figure 2) using data from USDA surveys (USDA NASS, 2018a). We chose to create a set of states that represented 90 percent of swine production during each year of the study period. Starting in 1960, 20 states represented 92 percent of production in terms of total swine inventory. Production in the industry has consolidated considerably since 1960, with 20 states containing 97 percent of production inventory by 2015. Although fewer states are needed to reach the 90 percent mark for every year after 1960, once a state appeared on the top 20 list in any year, it was included in each simulation year. Similarly, each county was kept for the all simulation periods, unless the number of hogs fell to zero as reported in the NASS data.

Once the list of states for the study period was determined, counties from each state were selected based on total inventory that was present in the "First of December" survey period as reported by USDA NASS. Each county within an individual state was ranked from highest to lowest, with the total inventory used as the sorting variable. The top county in the list for each year of available data in each state was added to the list of representative counties. This list was presented to industry experts, and some additional counties were added to the list in states where the geographic representation was inadequate, or else an important country of production had not been included in the original list. The final list included 84 counties in 24 states (Table 1 and Figure 3).

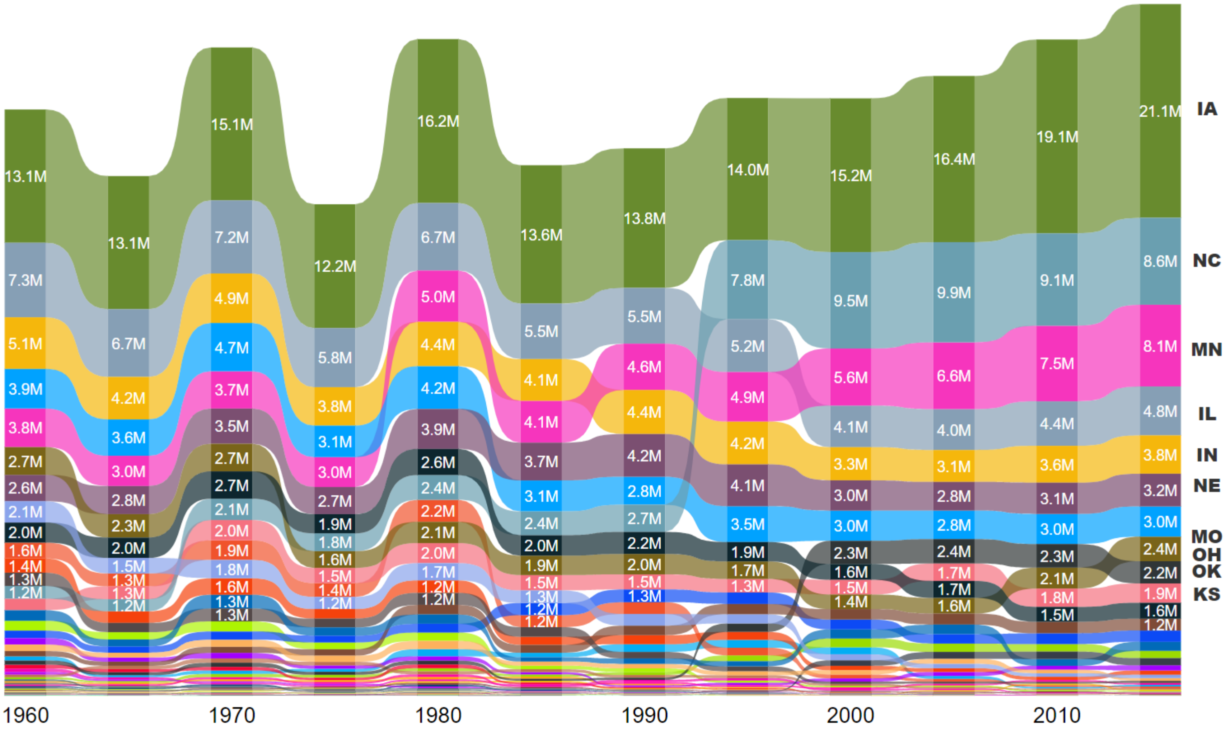

Figure 2. Ribbon chart showing the change in state ranking and state total inventory (million animals) across the simulation period. Select states are identified at right.

2.2.1.2 Weather

The standard version of the PPEFC only contains current weather data, so once the list of counties was determined, a unique set of weather files needed to be created for each county and for all simulation years. The PPEFC utilizes weather files in ten-year increments; however, because our simulation years are in five-year increments, we centered the weather files around the simulation year. For example, simulations for 1980 relied on five-year weather files using data from 1978 to 1982. The calculator was used to simulate the same five-year weather pattern two times sequentially, the first five-year timeframe was used to approach steady-state operation for manure management systems. The lifecycle inventory data used in the SimaPro model was taken as the average of the simulation results over the second five-year simulation period. The weather files from 1980 onward were created using data from NASA's MERRA data set (Rienecker et al., 2011). In the event that the MERRA data were incomplete, the weather files were supplemented by NOAA's Climate Data Online (NCDC, 2015). Satellite weather data does not exist prior to 1980; therefore, historical NOAA data, from weather stations located in the simulation county, for daily high and low temperatures were interpolated into hourly temperatures based on typical diurnal cycles. A custom computer program was written to extract the data from the MERRA files and translate into the appropriate input format for the calculator.

Table 1. A list of the 24 states considered for this assessment and the subsequent number of counties within each state that were simulated.

States	**Counties per state**	**County names**
Alabama……...	6	Covington, DeKalb, Henry, Houston, Pickens
Arkansas……...	4	Benton, Pope, Sevier, Washington
Colorado……...	4	Adams, Morgan, Weld, Yuma
Georgia……….	5	Bulloch, Coffee, Colquitt, Mitchell, Oglethorpe
Illinois………...	5	DeKalb, Edgar, Greene, Henry, Pike
Indiana………...	1	Carroll
Iowa…………...	5	Delaware, Hardin, Plymouth, Sioux, Washington
Kansas………...	3	Nemaha, Scott, Washington
Kentucky……...	4	Allen, Hopkins, Nelson, Union
Michigan…….....	2	Allegan, Cass
Minnesota……..	5	Fillmore, Freeborn, Martin, Nobles, Stearns
Mississippi…….	3	Hinds, Noxubee, Yazoo
Missouri……….	7	Lafayette, Miller, Nodaway, Pike, Saline, Sullivan, Vernon
Nebraska………	4	Cedar, Cuming, Holt, Platte
North Carolina...	2	Duplin, Sampson
Ohio…………...	3	Clinton, Darke, Mercer
Oklahoma……...	3	Canadian, Delaware, Texas
Pennsylvania…...	1	Lancaster
South Carolina…	3	Dillon, Horry, Orangeburg
South Dakota…..	3	Hutchinson, Lincoln, Minnehaha
Tennessee……...	3	Gibson, Henry, Weakley
Texas…………...	4	Archer, Fayette, Llano, Lubbock
Virginia………...	3	Rockingham, Southampton, Virginia Beach City
Wisconsin……...	1	Grant

2.2.1.3 Performance characteristics

Grow-finish barns in each simulation year modeled incoming piglets as weighing approximately 13 lbs. and in 1960 were finished at 200 lbs. Finishing weights increased steadily over the assessment period and in 2015 reached 282 lbs. As finishing weights increased, feed conversion ratio (FCR) was improving. In 1960, the average FCR was estimated to be 4.3 lbs. of feed per pound of LW produced. By 2015, the FCR had improved to 2.6. Mortality rates in the grow-finish barn were much less consistent over time, with the national average rate rising and falling throughout the assessment period. The piglets produced per sow and the number of piglets that survived to weaning increased over the assessment period. In 1960, sows were simulated as having ten piglets per litter with seven surviving to weaning. By 2015, those numbers increased to 13.5 and 10, respectively. Data were scarce with regard to the replacement rate of sows throughout the assessment period, so it was assumed that it remained relatively constant over the assessment period at 50 percent annually (Safranski, 2005). The same issue exists regarding the information available on the sow mortality rates. When robust data were available, we used

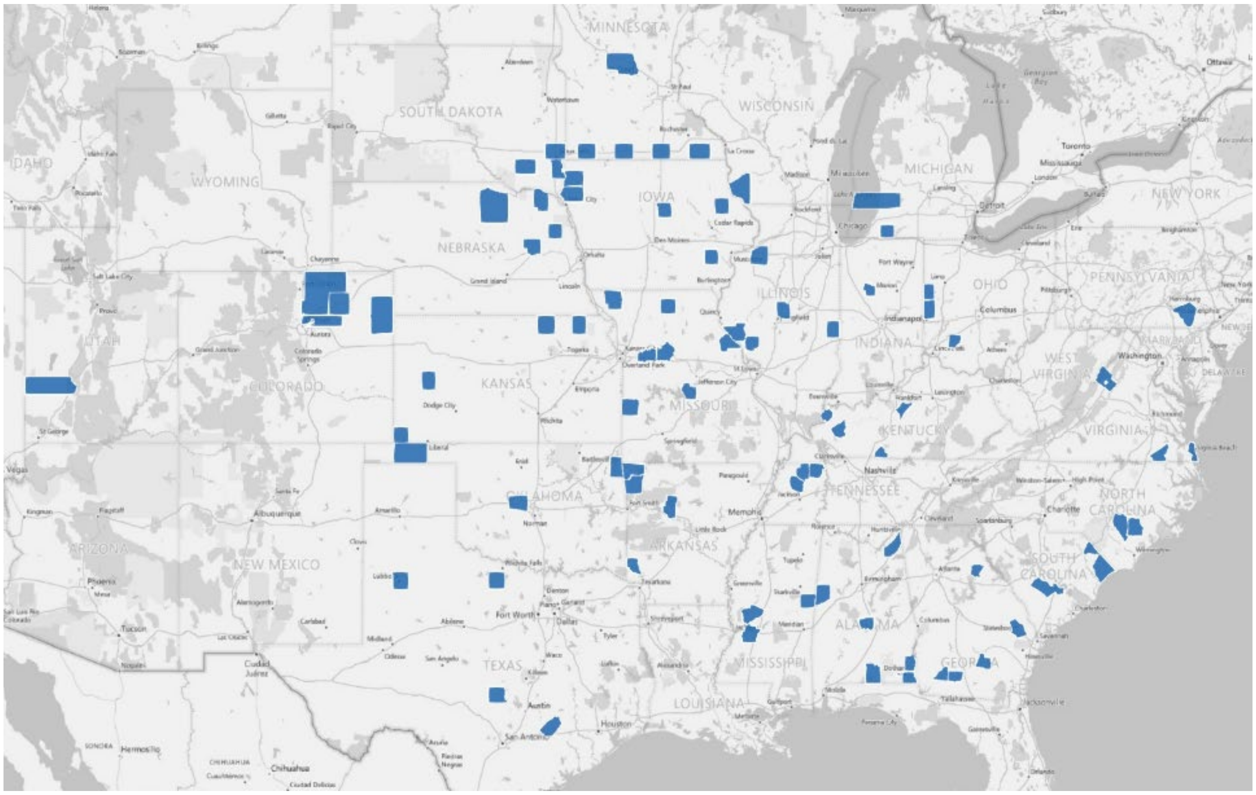

Figure 3. Locations of counties included in simulations, showing geographic coverage.

it to inform the PPEFC simulations (USDA, 2008). Otherwise, we used a default value of 3 percent. Key performance characteristics implemented in the grow-finish and sow barns are presented in Table 2. A full list of PPEFC input parameters are available in Appendix Table 1 for grow-finish barns, Appendix Table 2 for sow barns, and Appendix Table 3 for the overall farm.

2.2.1.4 Production facilities

Approaching the 1960s, permanent housing was most commonly used in breeding operations; however, these were minimal structures typically consisting of wooden walls and dirt floors. For large herds of grow-finish pigs, the most common approach was to use movable houses to protect against infection. These facilities were intentionally minimal so that they could be relocated around the pasture in order to prevent the concentration of manure (Bond and Peterson, 1958). The PPEFC is not capable of modeling such extensive farming practices, so to construct representative simulations for the 1960, 1965, and 1970 reference years, we created grow-finish and sow barns using the "hoop barn" designation. We set hoop barn parameters to exclude fans, piglet cooling equipment, and set the R value of the walls and ceiling to 0 (i.e., without any insulation). The only energy uses on farm for 1960, 1965, and 1970 were associated with lighting and piglet heaters in the sow barn, which were commonly used by producers in

Table 2. National average performance characteristics simulated in grow-finish and sow barns for each reference year.

Year	**Grow mortality (% pigs)**	**FCR**	**ADG (lbs./day)**	**Market weight (kg)**	**Days on feed**	**Piglets per litter**	**Weaned piglets per litter**	**Sow barn mortality (% annual)**
1960	1.8%	4.5	1.6	90.7	124.5	10.0	7.0	3.0%
1965	1.7%	4.6	1.6	95.3	134.2	10.1	7.2	3.0%
1970	1.7%	4.7	1.3	99.8	163.4	9.8	7.3	3.0%
1975	1.4%	4.7	1.4	105.2	162.9	9.2	7.3	3.0%
1980	1.4%	3.9	1.5	103.0	148.3	10.4	7.5	6.0%
1985	1.7%	4.1	1.5	103.0	155.3	9.2	7.3	6.0%
1990	2.0%	4.4	1.4	112.9	178.3	10.3	8.4	6.0%
1995	2.1%	3.5	1.8	116.1	142.5	10.0	8.5	9.0%**
2000	2.7%	3.2	1.8	118.8	146.2	10.8	8.8	12.0%**
2005	1.7%	3.0	1.7	122.0	162.4	11.8	9.4	1.0%**
2010	4.3%	2.8	1.6	121.9	168.3	13.0	10.0	3.0%
2015	1.7%	2.8	1.6	127.6	172.9	13.5	10.0	3.0%

** the fluctuations in sow mortality are primarily the result of changes in the reporting categories. The simulations in each year assumed a 50% replacement rate for sows (death + marketed). This variability falls below the 1% threshold requiring higher resolution data (USDA, 2008).

the United States during at least some part of the year. By 1975, hog farming was becoming more modernized, and the average size of an operation increased as more permanent facilities were constructed. Perhaps because of these changes, there is more thorough documentation of the United States pork industry beginning around this time. This improved documentation included detailed USDA reports covering the hog industry during the 1970s and 80s, enabling regionalized input parameters for the PPEFC during this time (Shapouri et al., 1988; Van Arsdall, 1978; White, 1983). The growth in pig industry during the 1970s occurred primarily in the Southeast, as hog farming spread outside of the Corn Belt. These newer operations were markedly different than their Midwest counterparts, making use of solid walled construction, and mechanized cooling, which were reflected in the southern county simulations beginning in 1975. Modernization of production facilities in the Midwest was not as widespread until the 1980s, and as such, this was not reflected in those simulations until 1985. By the early 1990s, most of the pigs produced in the United States were done so on modernized farms. As such, from 1990 onward, grow-finish and sow barns in all counties were modeled as fully enclosed barns with tunnel ventilation. A timeline summarizing the incorporation of certain PPEFC parameters regarding production facilities is presented in Table 3.

2.2.1.5 Manure management

Manure management systems were attributed to farms throughout the assessment period in a regionally explicit manner when the data supported such disaggregation from the national level data. Throughout the assessment period, data were not always available to differentiate between manure

Table 3. A summary of the simulation years in which changes were made to housing parameters in grow-finish and sow barns.

Year	Grow-finish barns	Sow barns
1960	*PPEFC uses "hoop barn" designation. No fans, heating, or cooling, but some lighting*	*PPEFC uses "hoop barn" designation. No fans or cooling, some lighting and heat lamps for piglets.*
1975	*PPEFC uses "drop curtain" designation for Southeast states. Includes fans, full barn heating with propane, and sprinkler cooling. No change in North Central states.*	*Southeastern states modeled as "tunnel ventilated", all others "drop curtain". Both include fans and full barn heating with propane.*
1985	*All counties in PPEFC get "tunnel ventilated" designation, which includes fans, sprinklers, and full barn heating with propane.*	*No change to sow barns*
1990	*No change to grow-finish barns*	*All counties in PPEFC get "tunnel ventilated" designation, which includes fans and full barn heating with propane.*
After 1990	*All counties in PPEFC remain "tunnel ventilated" designation*	*All counties in PPEFC remain "tunnel ventilated" designation*

management systems of piglet producers (sow barns) and grow-finisher operations (grow-finish barns). To retain a consistent approach throughout the assessment period, data were compiled for market pig producers and applied to both sow and grow-finish barns in a region. While we know from the data that this is not always the case, the lack of data availability throughout the period in conjunction with the lower contribution of sow barns to the footprint of LW swine, we are confident that this assumption will not alter the conclusions drawn from these results. The distribution of manure management systems in each region over time is shown in Figure 4. The best available data showed a significant, and somewhat anomalous, fraction of liquid slurry management in 1995; we do not have other information regarding this system but simulated it as an outdoor lagoon.

As mentioned in the previous section, manure management systems in the 1960s were predominantly open lot and dry bedding systems. The PPEFC does not simulate pasture-raised pigs, and therefore the first three reference years were treated as dry bedding systems in the PPEFC. Only by the mid-1970s with the shift towards industrial hog farming does the use of intensive manure management systems start to receive mention in the literature. The dominant system in the 1975 and 1980 simulations remained dry bedding, but other systems were starting to place the pasture-based operations, and by 1985 the use of dry bedding dropped below 50 percent of all United States operations. In the North Central United States, dry bedding systems were replaced by slatted flooring, which typically diverted manure to

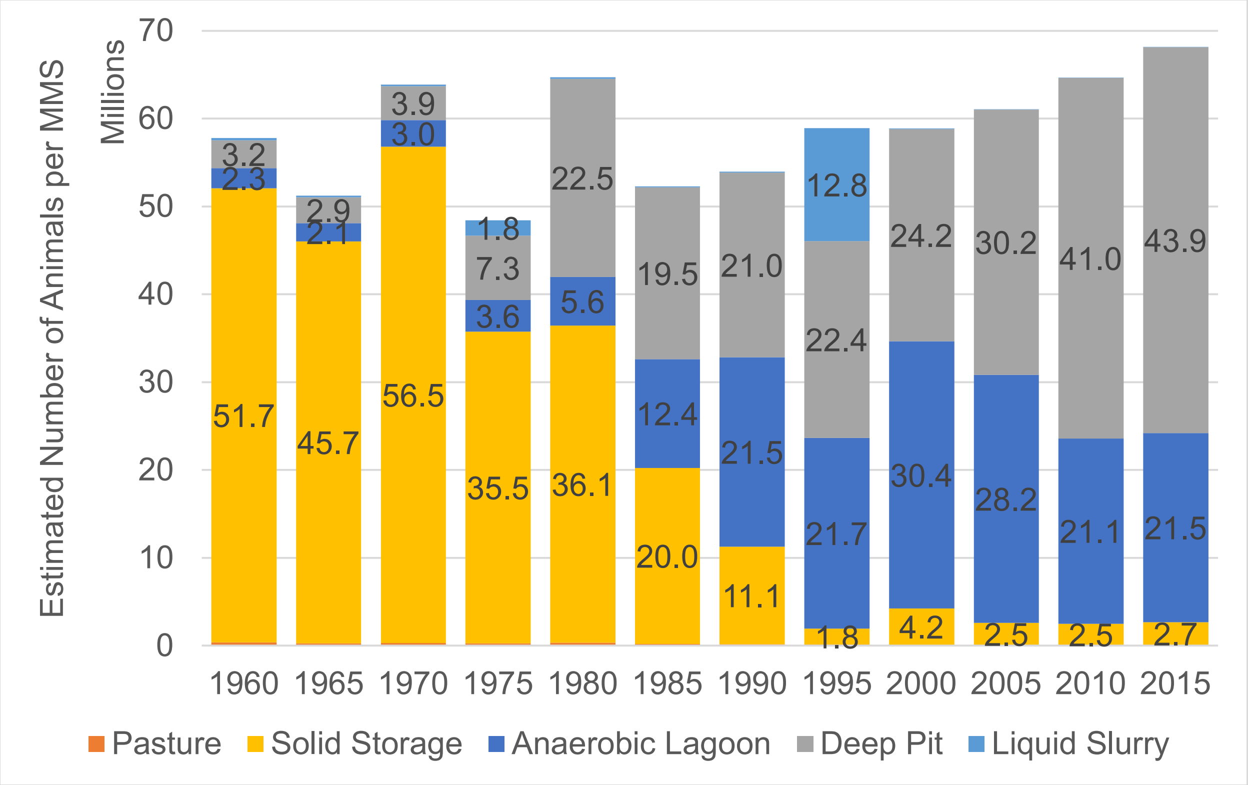

Figure 4. Distribution of hogs among manure management systems. State level data regarding number and type of manure management was used in simulations. Here is inventory-weighted distribution of manure management at national level.

a subfloor or a deep-pit. In the Southeastern United States, disposal of swine manure into lagoons became more and more common, reaching its highest level of adoption in the 2000 simulation with 78 percent of farms in the SE using anaerobic lagoons for managing manure. New regulations increased restrictions on manure management practices which slowed expansion of the industry. As a result, new farms (and newer manure management systems) were not built during this time, and the Southeast simulations continue to utilize lagoons at +90 percent throughout the remainder or 1990s. Not until the early 2000s do the data suggest a decline in the use of lagoons. The 2005 Southeast simulation represents the first decrease in manure managed in lagoons for the region since the shift from pasture raised pigs in 1975. The use of lagoons to manage manure increased over the same period in other areas of the United States as well, but not to the same extent as in the Southeast. North Central producers have been much more likely to rely on deep-pit systems, and that has continued up to current day with the 2015 North Central simulation attributing deep-pit management to 75 percent of producers.

2.2.1.6 Feed rations

Feed rations for the PPEFC were based on the nutritional values published by the National Research Council (NRC) in the Nutrient Requirements of Swine publications (National Research Council, 2012, 1998, 1988, 1979, 1973). The initial ration formulation and list of ingredients was adopted from the 1973 publication as it was earliest edition available. That initial formulation was used in the simulations for 1960 – 1975, and from then on, the edition published closest to the reference year was used. Feed rations were formulated using these nutrient requirements and an initial set of ingredients, which consisted of corn, soybean meal, minerals, and vitamins (Table 4). For sow barn rations, we formulated two distinct rations: one for gestating sows and one for lactating sows. For grow-finish barn rations, we formulated multiphase rations that followed the number of phases given in the NRC publication of reference to reach the market weight of each simulation year.

Table 4. A list of the changes made to the base ration over the assessment period and the simulation year in which those changes were implemented.

Simulation year	Description
1960	Base ration formulated using guidelines from NRC (NRC 1973). Includes corn, soybean meal, dicalcium phosphate, limestone, salt, vitamin/mineral mix
1970	Addition of poultry fat and two crystalline amino acids (Lysine and Methionine)
1980	Rations reformulated using updated nutrient recommendations (NRC 1979)
1985	Addition of two more crystalline amino acids (Tryptophan and Threonine)
1990	Rations reformulated using updated nutrient recommendations (NRC 1988)
1995	Soybean meal changed to dehulled, moving from 44 percent to 48 percent crude protein
2000	Addition of Ractopamine into grow-finish barn rations, updated nutrient requirements (NRC 1998)
2005	Addition of DDGS
2010	Addition of crystalline amino acid Valine and updated nutrient requirements (NRC 2012)

The spreadsheet-based ration optimization tool WUFFDA 2.1 was used to determine the ration formulations each of the grow-finish and sow barn diets in a given simulation year (Alhotan and Pesti, 2016). Nutrient requirements for each phase were entered into the WUFFDA calculator along with the list of available ingredients. Each available ingredient was assigned a set of parameters which described its nutrient contents, its minimum and maximum inclusion rates for each phase, and its price. We used the nutrient profiles of each ingredient from the same NRC publication which informed the swine nutrient requirements for that simulation year. The price data was primarily informed by data from the USDA (USDA ERS, 2018a; USDA NASS, 2018). If data were not available for the entire time period of this assessment, prices were linearly interpolated to fill in the price data for missing years. For ingredient prices that were not tracked by government databases or did not otherwise have consistently available historic pricing data we used recent pricing data and interpolated back in time according to established pricing trends of ingredients that served similar purposes in the ration. For example, historic price data on synthetic amino acids was unavailable, so the current price was interpolated back in time according to the trend in price for soybean meal because they often offset a source of crude protein in the diet.

While swine diets have become more homogenous over time, corn and soybean-based diets have been commonly used since 1960 (Becker, 1959; Carlisle and Russell, 1970; Van Arsdall, 1978). As such, those two commodities were selected as the primary ration constituents for the entire assessment timeframe; however, the list of included ingredients was expanded over time. Using information available in the literature and consultation with industry experts, the list of ingredients for rations was expanded according to what was considered common practice at the time. Table 4 gives the ration ingredients and the year in which their inclusion in the rations began. Except for the inclusion of dried distillers' grains (DDGS) into diets, we did not formulate rations with different ingredients within the same reference year and for the same barn type. All grow-finish barns in any given year, regardless of location, were fed the same ration. While we recognize that this is not likely the case, we were unable to find information to provide guidance into regional ration formulations, particularly as the simulation year approaches 1960. However, DDGS presented a special situation.

DDGS, a co-product of ethanol production, are used in animal diets to substitute corn and soybean meal. The production of ethanol and consequently that of DDGS saw a rapid increase after year 2001; therefore, DDGS were included in the diets of pigs starting in year 2005 of our simulations (Wisner, 2010). Hoffman and Baker (2011) recommend including DDGS in swine diets at the inclusion rate of 10 to 50 percent of dry matter for breeding swine and 10 to 30 percent of dry matter for market pigs. The recommended DDGS substitution rate for corn and soybean meal is 0.7 to 0.89 and 0.1 to 0.3 pounds per pound of DDGS respectively. Stein and Shurson (2009) reported that up to 30 percent DDGS can be included in nursery and grower-finisher pig diets without affecting pig performance. However, high linoleic acid in DDGS can make pork fat softer and therefore Stein and Shurson recommended limiting DDGS inclusion rate in finisher diets to 20 percent and weaning pigs off DDGS in last three weeks. For breeding pigs up to 30 and 50 percent DDGS can be included in lactation and gestation diets respectively (Stein and Shurson, 2009). The authors also recommended fortifying diets with amino acids when DDGS are included.

According to Renewable Fuel Association (RFA), biorefinery sector in the United States produced 7.9 million metric tons of distiller's grains for animal feed in 2005 and by 2015 that number increased to 35.5 million metric tons (RFA, 2018a). The RFA estimated that 16 percent of DDGS[2] in the United States were consumed by swine industry; however, estimates on actual DDGS consumption by pigs in the United States were inconsistent[3] (Gottschalk, 2007; RFA, 2018a). Following the inclusion guidelines published by Hoffman and Baker (2011) and Stein and Shurson (2009) and applying the WUFFDA formulated diets to ALL pigs produced in final three simulation years resulted in the total national consumption of DDGS to be significantly larger than estimated consumption in 2005, but still below the 16 percent consumption rate reported by RFA, but approximately equivalent to the 9 percent consumption rate reported in a 2007 study[3]. This is an important consideration as the inclusion of DDGs in the ration is associated with an increase in energy use and GWP, and the total quantity consumed therefore has an important effect on the national, sector level estimates. Therefore, for the sake of representativeness and consistency, diets formulated by an animal nutritionist at the University of Arkansas were used for the final three simulation years and two feed ration scenarios were considered.

Two scenarios for years 2005, 2010, and 2015 were created using the diets formulated to include and exclude DDGS. In the first scenario (All DDGS) it was assumed that DDGS were fed to 100 percent of pigs in all the counties used in the study; these results are not included in this report, as they are not considered representative of the industry. However, an online, interactive report will be made available in which this scenario is included. In the second scenario (Limited DDGS), pigs in some counties were assigned diets with DDGS while those in other counties were assigned diets without DDGS. Use of DDGS in 2005 was limited to Southern Minnesota and North and Central Iowa and to have expanded to other pork production regions in 2010 based on ethanol biorefinery locations at the time – see Figure 5 (RFA, 2018b). Diets formulated to include DDGS were assigned to a simulated farm if an ethanol biorefinery was located in that county or a neighboring one.

---

[2] http://www.ethanolrfa.org/resources/industry/co-products/#1456865649440-ae77f947-734a

[3] https://beef.unl.edu/beefreports/symp-2007-01-xx.shtml

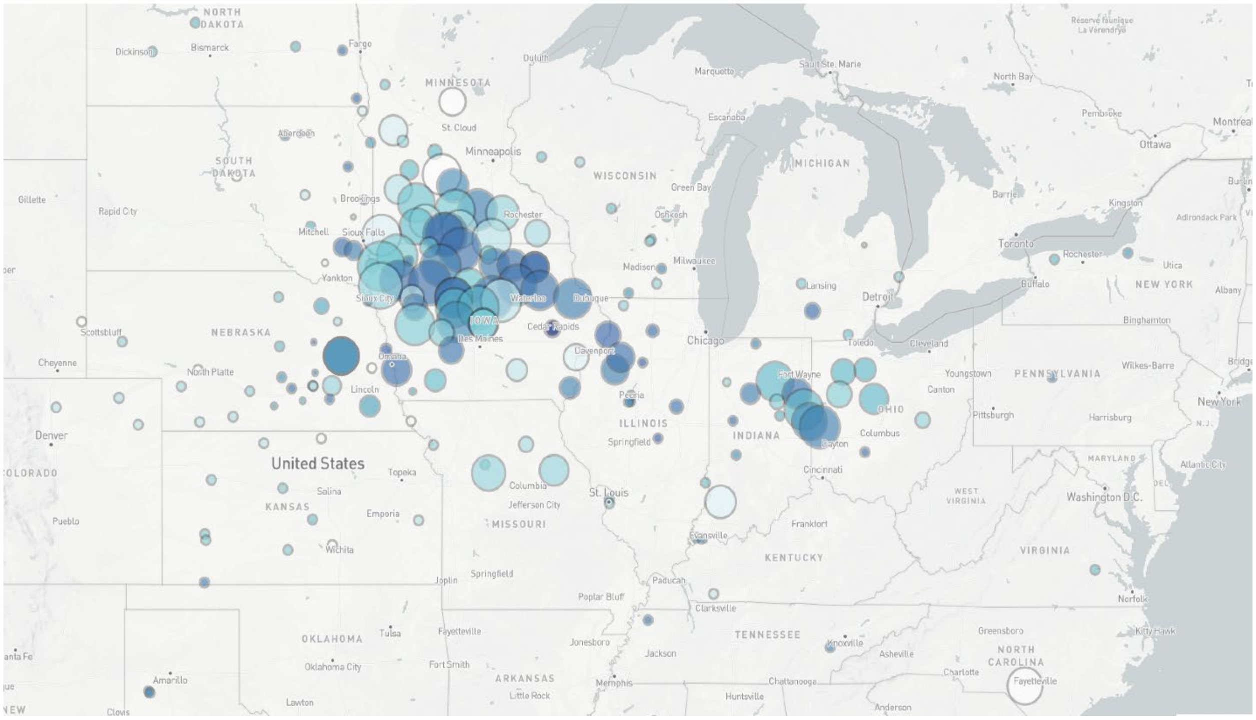

Figure 5. Distribution of hog production with proximity to ethanol production facilities. The size of the circle represents the relative number of hogs sent to market in a county, and the color represents the quantity of distillers' grains produced in the same vicinity. Darker shades represent higher production of distillers' grain. For the limited DDG scenario, counties in regions distant from a source of DDG were fed a corn/soy ration formulated without DDG.

2.2.2 Feeds

We have included the best approximation of typical swine feeds over what is available in the literature and consistent with available lifecycle inventory. In the 1960s some wheat, oats and alfalfa was fed to pigs as an energy feed which eventually shifted to a primarily corn/soy and more recently corn/soy/DDGS ration. Due to the lack of data regarding production of the alternate ingredients in the earlier years, we formulated corn/soy rations for the entire period, with inclusion of DDGs beginning in 2005. The following sections outline the sources and data used for estimating the impact of ration ingredients.

2.2.2.1 Crops

Life cycle inventory (LCI) data for crop production were collected from each of the top five corn and soybean producing states in the United States Illinois, Indiana, Iowa, Minnesota, and Nebraska were the top five throughout the assessment period, and combined they produced 59 to 68 percent and 47 to 61 percent of all U.S. corn and soybeans, respectively (Figure 6). USDA survey data from these states were used to determine LCI data for yield and production volume (USDA NASS, 2018). Fertilizer application

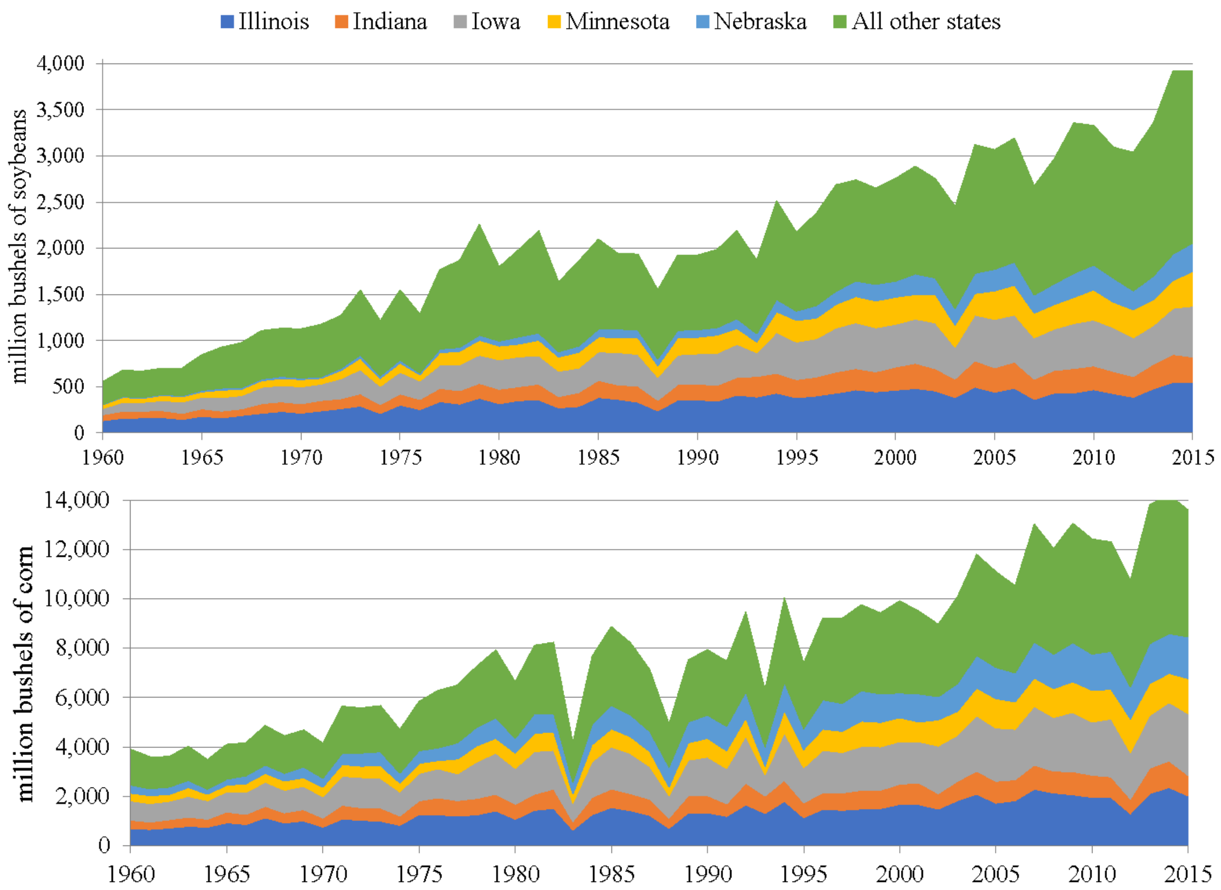

Figure 6. Corn and soybean production over the assessment period from the five states from which data were used to inform the corn and soybean LCI processes along with production from the rest of the United States.

rates were determined using data from NASS Agricultural Chemical Usage for years 1960 to 2010 (USDA ERS, 2018b). Pesticide use for the same time period was determined using a dataset published by the USDA (Fernandez-Cornejo and Vialou, 2014). Emissions associated with nitrogen fertilizer applications and crop residues were calculated using IPCC methods (Intergovernmental Panel on Climate Change, 2006). Fuel use associated with planting, irrigating, and harvesting was estimated using crop budgets published by extension services in each of the five states. Since a comprehensive set of historic crop budgets was not available, fuel use was adjusted for each simulation year according data from tractor efficiency tests published by the Nebraska Tractor Test Lab (Hoy et al., 2014). The methods and sources used to determine tractor efficiencies for this assessment are described in detail in Section **2.2.3.2.** Data from all five states were used to inform production-weighted LCI models for corn and soybean cultivation, representing national production during each simulation year. A summary of LCI values used in the corn and soybean models are presented in Table 5 and Table 6.

Table 5. A summary of LCI values used in the corn unit process for each simulation year.

Year	Yield (kg)	Irrigation water (m^3)	Pesticides (kg)	Nitrogen fertilizer (kg N)	Phosphorous fertilizer (kg P)	Potassium fertilizer (kg K_2O)	Diesel (l)	N_2O emissions (kg)
1960	3,921	152.06	0.38	55	35	28	76	1.75
1965	5,330	190.09	1.01	77	48	42	74	2.38
1970	5,015	246.95	1.70	124	75	73	75	3.32
1975	6,080	314.61	2.47	115	57	64	78	3.28
1980	6,188	361.56	3.60	143	66	81	81	3.86
1985	7,969	327.42	3.63	163	59	75	77	4.52
1990	7,954	281.24	3.91	153	59	72	74	4.30
1995	7,317	264.87	3.30	145	53	65	72	4.07
2000	8,998	209.66	2.53	154	58	70	66	4.47
2005	10,067	438.72	2.37	153	57	77	83	4.58
2010	10,310	302.76	1.32	161	58	64	82	4.77
2015	11,411	389.15	1.70	167	79	94	79	5.06

Table 6. A summary of LCI values for the soybean unit process for each simulation year.

Year	Yield (kg)	Irrigation water (m^3)	Pesticides (kg)	Nitrogen fertilizer (kg N)	Phosphorous fertilizer (kg P)	Potassium fertilizer (kg K_2O)	Diesel (l)	N_2O emissions (kg)
1960	1,699	5.06	0.12	0.6	3.7	4.3	41	0.52
1965	1,793	6.24	0.37	1.3	5.0	7.1	39	0.55
1970	2,053	8.00	0.93	2.6	8.5	14.4	39	0.62
1975	2,254	11.45	1.52	2.1	7.2	11.6	40	0.64
1980	2,355	23.34	2.21	2.2	11.1	17.2	39	0.66
1985	2,630	33.99	1.49	2.3	9.4	20.6	37	0.70
1990	2,671	31.24	1.57	3.9	10.5	22.6	36	0.74
1995	2,719	34.57	1.24	4.1	11.4	22.4	36	0.75
2000	2,891	56.82	1.22	4.0	8.9	22.6	36	0.78
2005	3,296	198.67	1.42	3.8	13.1	26.6	46	0.84
2010	3,356	132.81	1.97	3.2	13.9	26.2	45	0.83
2015	3,667	179.44	1.52	4.7	18.6	34.3	44	0.91

2.2.2.2 Irrigation water

Irrigation water use was calculated for each year using multiple sources because no single source exists that links production of an individual crop within a state to the total quantity of irrigation water applied. Further complicating matters, the USDA census reports supply the best available data on irrigated acreage in the United States; however, these reports were not published on a consistent time period. As such, irrigation water use in corn and soybean production was calculated using a combination of USDA census reports and USGS water reports. The USGS water reports were published every five years and were representative of the same years as our simulation years, so they were used inform the quantity of water applied to crops (Hutson et al., 2004; Kenny et al., 2009; MacKichan and Kammerer, 1960; Maupin et al., 2014; Murray, 1968; Murray and Reeves, 1977, 1975, Solley et al., 1985, 1998, 1993, 1988). For years 1960 to 1975, the USDA census reports were published for the year prior to each simulation year, so they were used in combination with the USGS reports to link the quantity of water to the cropland on which it was applied (Hurley and Mcpike, 1959; USDA, 1978, 1973, 1967). For years 1980 to 2010, the census publications shift years, making them even less representative of the simulation years chosen for this assessment. In order to align irrigation water in our crop models with these simulation years, we averaged the data from the two census reports nearest to the simulation year (USDA, 2009, 2004, 1999, 1996, 1989, 1984, 1981). For example, the 1985 crop models utilized data from the USDA census reports from 1982 and 1987 in combination with water use data from the USGS report from 1985. It should be noted that as a result, most of the census reports were utilized in two crop models, e.g. the 1987 report informed both the 1985 and 1990 crop models. At the time of this assessment, the most current USDA census report was 2012; therefore, irrigation water in the 2015 crop models was informed solely by the Farm and Ranch Irrigation Survey from 2013 (USDA, 2014).

2.2.2.3 Crop by-products

The production of DDGS was represented by adapting an existing USEI unit process for an ethanol distillery with the temporal corn model described in the previous section. Allocation of corn production impacts between DDGS and ethanol was performed at the ethanol distillery. Further processing, such as natural gas used in the drying of DDGS was attributed exclusively to the DDGs.

Two unit processes for soybean meal were created using the temporal soybean crop model as an input to an existing unit process from the USEI database. One of these unit processes was constructed such that soybean meal and oil were the only two coproducts, and this process was used for soybean meal in simulations for 1960 through 1990. Around the mid-1990s, it became more common for soybean processors to separate out the hulls from the meal, which increased the crude protein content from 44 percent to 48 percent (Cromwell, 2017). As such, simulations starting in 1995 utilized soybean meal from a different unit process in which hulls were included as a third product. As a result, slightly less de-hulled soybean meal was produced for the same input of soybeans, which also altered the allocation fractions (CME Group, 2012). Aside from this change in 1995, it was assumed that the material and energy requirements for processing soybeans have not changed substantially since 1960 and that these adapted USEI processes provided accurate representations of soybean processing throughout the assessment.

2.2.2.4 Poultry by-products

The NRC recommendations for swine nutrition have become more prescriptive over time, and as a result, our feed ration formulations required additional ingredients to meet these requirements. Developments in the understanding of piglet nutrition led to nutrient profiles that could not be met by corn- and soy-based feeds alone. In order to meet the evolving nutrient requirements of nursery rations throughout the assessment period, results from a poultry retrospective covering a similar timeframe were adapted for use in this assessment (Putman et al., 2017). Poultry by-products were modeled by interpolation of production in the 1960s and the 2010s to the simulation year.

2.2.2.5 Other feeds

Non-agricultural feeds like vitamins and minerals were represented by unit processes from the U.S. Ecoinvent v2.2 (USEI) database (Frischknecht et al., 2005). We assumed impacts associated with the production of these items remained constant over the assessment period. While this is likely to underestimate their contribution to potential impacts, particularly in the earlier simulation years, it is unlikely to undermine the robustness of conclusions drawn from the results of this assessment as these items are consumed in such small quantities and do not contribute significantly to environmental impacts associated with pork production.

2.2.3 Background systems

In addition to the non-agricultural feeds, the USEI database was used to estimate the upstream impacts associated with background systems, i.e. energy, transportation, and raw material production. Many of the standard unit processes within the database were adapted to reflect the changes in efficiency over time. Using historical data, regression equations were developed and applied to unit processes such that the efficiency could be adjusted to represent the simulation year. Table 7 provides an overview of the processes that were adapted. Production efficiencies of all other processes not listed in Table 7 were

Table 7. The types of processes that were adapted to reflect changes in efficiency over the assessment period are presented alongside the total change in process efficiency from 1960 to 2015 and the data source used to calculate scaling factors.

Process	**Efficiency change**	**Source**
Tractor fuel use	31%	Nebraska Tractor Test Lab
General use motors	25%	Nebraska Tractor Test Lab
Nitrogen fertilizer production	33%	International Fertilizer Industry Association
Road transport	18%	US Department of Energy
Rail transport	209%	US Department of Energy
Water transport	69%	US Department of Energy

assumed to be constant over the assessment period; however, the composition of power generation sources for the electricity grid mix was altered to represent the historical mix of a given simulation year. The methods and sources used to determine the changing efficiencies of these background systems are described in the following sections.

2.2.3.1 Fertilizer production

A report by the International Fertilizer Industry Association provided the energy efficiency of ammonia production plants from 1955 to 2008 (IFA, 2009). The data in this report was used to derive a regression equation relating production efficiency to simulation year. This equation produced scaling factors for each simulation year, which were applied to the energy requirements within the USEI unit processes for nitrogen fertilizer production.

In addition to the changing production efficiency, the types of nitrogen fertilizers used in United States agriculture also changed. In order to account for the various types of nitrogen fertilizers used throughout the assessment period, a national average mix was compiled for each simulation year using data from the USDA ERS (USDA ERS, 2018b). Each type of fertilizer was represented in the model using processes from USEI, each adjusted for production efficiency with respect to the simulation year.

2.2.3.2 Tractor efficiency

According to data from the Nebraska Tractor Test Laboratory, fuel consumption in the tractors sold in the early 1960s was 31 percent higher for drawbar power and 25 percent higher for power take-off than of those sold in the early 2010s. Based on the data from this assessment, regression equations were developed linking fuel consumption for crop-related operations to the simulation year. Drawbar power was used to develop the equation for fuel use efficiency in field operations and power take-off served as a proxy for general use motors. Using this set of equations, we were then able to estimate fuel consumption in crop production that reflected the efficiency of equipment with respect to the simulation year.

2.2.3.3 Transport modes

The Transportation Energy Data Book published statistical data for the energy intensities of freight modes going back to 1970 (Davis et al., n.d.). Linear regressions were developed using this data to extrapolate back to 1960, and forward to 2015. These regressions were used to create scaling factors for transportation via road, rail, and water. These scaling factors were used to adjust the fuel use per ton-km of each transport unit process throughout the supply chain.

2.2.3.4 Electricity mix

All unit processes within the USEI database that utilize electricity from the United States power grid are linked to a single upstream process that represents an average mix of power generation sources for the nation. By altering this mix, we were able to create a representative electricity mix for each simulation year based on historical data published by the United States Energy Information Administration (US EIA, 2014). While the mix of sources of power generation in each simulation year changed, the efficiency of each was not altered. While this will likely underestimate the impacts from electricity, particularly in earlier years, it is unlikely to alter the conclusions drawn from the results of this assessment. Additionally, despite efficiency changes not being reflected, the representative mixes will likely provide insight to the changing impacts through time that a static mix would not. The makeup of power generation sources in the electricity grid used in each simulation year is shown in Table 8.

Table 8. The percent contribution of electric power generation by source as implemented into the LCA model for each simulation year.

Year	Coal	Petroleum	Natural gas	Nuclear	Hydroelectric	Wind	Other renewables
1960	53.3%	6.4%	20.9%	0.1%	19.3%	0.0%	0.0%
1965	54.1%	6.1%	21.0%	0.3%	18.4%	0.0%	0.0%
1970	46.0%	12.0%	24.3%	1.4%	16.2%	0.0%	0.1%
1975	44.5%	15.1%	15.6%	9.0%	15.6%	0.0%	0.2%
1980	50.8%	10.8%	15.1%	11.0%	12.1%	0.0%	0.2%
1985	56.8%	4.1%	11.8%	15.5%	11.4%	0.0%	0.4%
1990	54.2%	4.1%	10.7%	19.9%	9.9%	0.1%	1.2%
1995	52.8%	2.1%	13.2%	21.1%	9.5%	0.1%	1.2%
2000	53.4%	2.9%	14.3%	20.7%	7.3%	0.2%	1.2%
2005	51.1%	3.0%	17.7%	20.1%	6.7%	0.5%	1.0%
2010	46.1%	0.9%	22.8%	20.3%	6.4%	2.4%	1.1%
2015	34.3%	0.7%	31.7%	20.4%	6.2%	4.9%	1.9%

2.2.4 Aggregation

In order to calculate the national impacts from county-level results, a methodology for aggregation was established. For a given simulation year, impacts per kg LW were calculated for each state by calculating the production-weighted average of all the counties simulated in that state. These state-level impact averages for the 24 states with simulated counties were then multiplied by the LW production of each state for the simulation year using data from the USDA to get the total impact from each state (USDA NASS, 2018). Results from the 24 simulated states were used to create production-weighted average impacts to serve as national average impact per kg LW marketed. The production-weighted average national impact values were used in determining the impacts associated with pig production in the remaining 26 states. The equations used for aggregation are given in the appendix.

2.2.5 Allocation

Whenever possible, allocation was avoided by system expansion. This was required in two situations in the assessment. The first was regarding the culled sows leaving the sow barn. Since these animals enter the human food supply, they were incorporated into the functional unit in proportion to their direct contribution to finishing one market weight pig from the grow-finish barn. The ratio of culled sows to market weight pigs was established using the ratio in the following equation, which is inclusive of the entire life of a sow, weaned piglets, and finished pigs, accounting for mortalities.

$$\frac{kg\ LW\ Sow}{kg\ LW\ finisher} = sow\ \ weight\ (kg)\left[\frac{\#\ culled\,\frac{sows}{yr}}{\#piglets\,\frac{weaned}{yr}}\right][1 - grow/finish\,mortality]$$

In addition to including culled sows, we also expanded the system boundaries to include the emissions from field application of manure after the on-farm treatment or storage stage. This accounting ensures a consistent system boundary across the entire temporal series. When agricultural byproducts were included as feeds, such as soybean meal, allocation was unavoidable. For soybean meal, we allocated according to the mass-adjusted energy content of the coproducts, which allowed the allocation fractions to remain constant across simulation years. Allocation of corn production impacts between DDGS and ethanol was performed according to the economic value of the two coproducts.

2.2.6 Life cycle impact assessment (LCIA)

Life cycle impacts were calculated using the SimaPro software platform. The GWP was determined using IPCC 100a 2013 characterization factors (Myhre et al., 2013). Energy use was determined using the method Cumulative Energy Demand v1.09 (Frischknecht et al., 2007). Water use was determined as strictly an inventory of water consumed, which does not include water uses like that of hydroelectric power plants. Land use was also calculated as strictly an inventory item, thus does not include potential effects on ecosystem services.

3 Results and discussion

The LCIA results for the simulated states are presented in Figure 7 with a basis of one kg LW pig at the farm gate in five-year intervals, starting in 1960 and ending in 2015. On average, impacts declined across all four categories over the assessment period. The largest decrease was seen in land use (75.9 percent), followed by water use (25.1 percent), then GWP (7.7 percent), and finally energy use (7.0 percent). Broadly speaking, this is an analysis of an extremely complex and inter-connected system which makes it challenging to quantify the specific contribution of individual factors that have influenced these

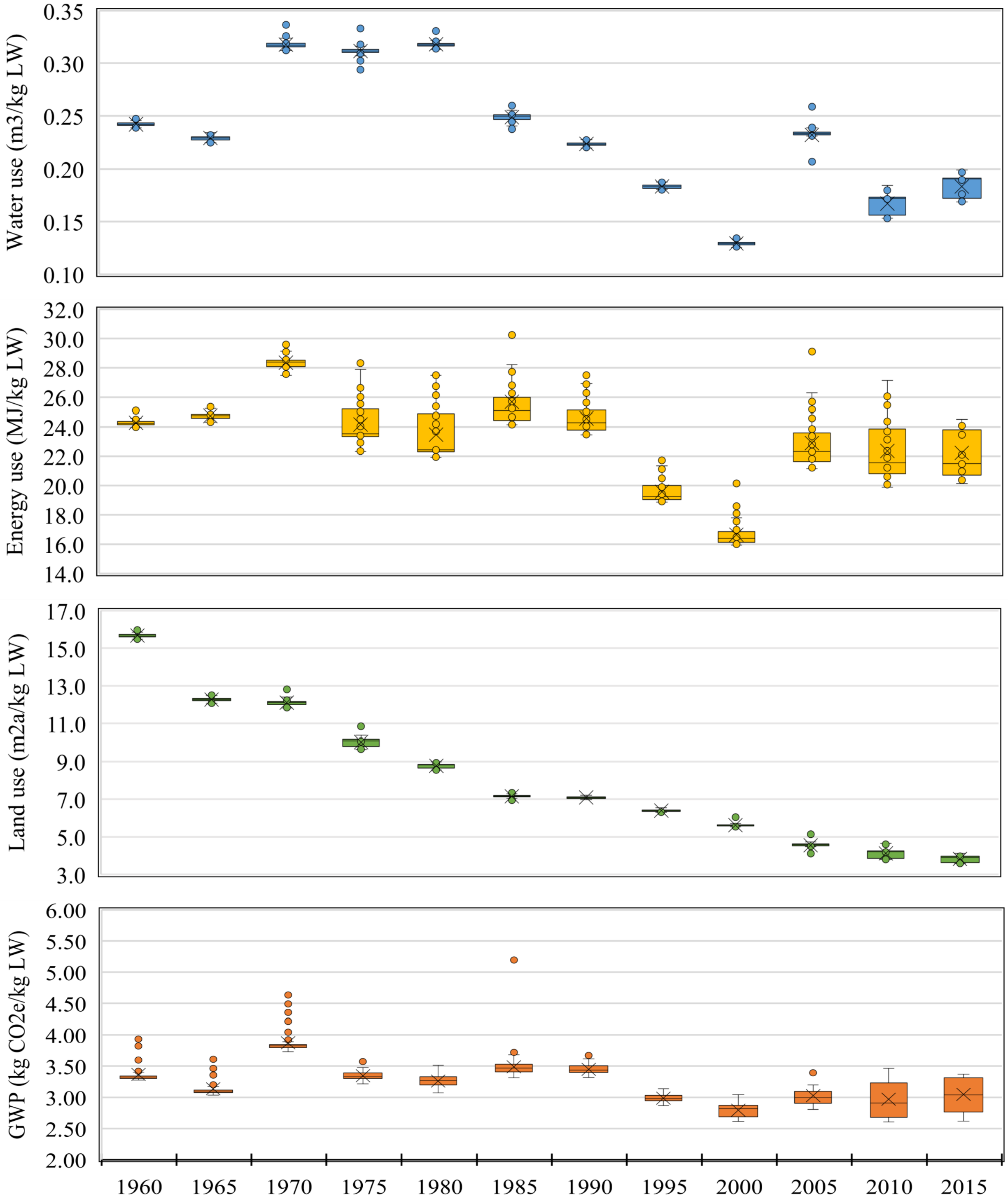

Figure 7. LCIA results for all the simulated counties. Boxes represent 50 percent of simulated counties, with the center line representing the median and the X representing the mean. Whiskers are the expected minimum and maximum values. Circles represent outliers, defined as being more than 1.5 times the interquartile range (size of the box) above or below the box

improvements. In addition to improvements in on-farm management, there are economy-wide changes in energy efficiency and manufacturing which also contributed to the improvements. In the following section, we attempt to identify major shifts and the effect these shifts have had on the performance metrics.

The GWP results have a higher variance during the period from 1960 to 1970 due to the extensive nature of pig production during those years. Manure emissions from pigs raised in warmer, southern states were higher than those in the northern states because methane volatilization increases with higher temperatures. This variability decreases in the 1970s and 1980s as production facilities become more advanced and manure storage moves indoors. This transition has the opposite effect on energy use, which had been relatively constant across states, but energy use begins to increase as fully enclosed production gained prevalence in southern states. The more modernized facilities initially led to larger energy use per kg LW with increased electricity and propane use for climate control, but over time these advances contribute to improved pig performance and subsequently lead to reductions in impacts associated with production. As production in other regions follows suit, the variability declines as facilities throughout the United States are increasingly homogeneous.

Starting around 1980, a significant fraction of production moved indoors, and facilities became more advanced, allowing for greater control over the production environment. With improvements in facilities came improved health and nutrition; as a result, impacts per kg LW declined across the United States from 1980 until 2005 in all impact categories. This trend reversed in 2005, which saw the introduction of distillers' grains into swine diets. The drying energy required to produce DDGS is associated with higher GHG emissions and energy use than the feeds replaced, causing an increase in the GWP and energy use associated with pigs having DDGS in their diets. Not all pig production takes place near ethanol facilities, which produce the distillers' grains as a byproduct, and therefore the variability in GWP and energy use increases in the 2000s as some rations include DDGS and others do not. The increase in water use in 2005 is not directly related to the introduction of DDGS. Instead, the corn and soybean models in 2005 rely on data from a significant drought year, which resulted in higher irrigation rates than normal. This explains the decline in the following years, which experience more normal weather patterns.

Land use associated with pig production was approximately 99 percent from crop production and this was consistent for production across the United States and throughout the assessment period. The stable decline in land use is representative of the improvement in domestic corn and soybean yields. The lack of variability within years is due to the corn and soybean models, which were not regionally explicit;

therefore, all animals in a given year were fed the same, national commodity average corn and soybean feeds regardless of their location.

3.1 Global warming potential

The influence of feed rations on the GWP per kg LW is significant, with the contribution of grow-finish barn feed to the GWP per kg LW pig ranging from 59 percent in 1970 to as low as 44 percent in 1995 (Figure 8). The peak impact of feed in 1970 is driven by corn production, which experienced a drought year that drove yields down while nitrogen fertilizer application rates remained largely the same. This led to relatively higher global warming impact from nitrogen fertilizer production and application emissions relative to other years. The high GWP of corn in 1970 is compounded by the FCR, which in 1970 is the highest (meaning worst performance) of any simulation year. In this case, 1970 was a drought year; however, it should be noted that this effect can also occur when a drought year falls within the timespan of the underlying data used to create the crop models. Following 1970, improving FCR and crop yields decreased the contribution of feed rations to the overall GWP to its low point in 1995. In 2005, grow-finish barn feed moves back above 50 percent of the total GWP per kg LW as DDGS are introduced into rations.

Emissions from manure in the grow-finish barn increase over the assessment period. Their relative contribution to GWP is as low as 10.9 percent (1980) and reaches 22.6 percent by 2015, as shown in Figure 9. While these emissions are influenced by numerous factors, i.e. nitrogen content of feed rations, manure management system, temperature, etc., the increase over time is mostly associated with the increase in finishing weights. As pigs are finished at heavier weights, in general, they spend more time in the grow-finish barn and produce more manure during their life. Since they are less efficient at converting feed into body mass as they mature, the manure excretion and thus emissions increase relative to the marginal increases in finish weight. The emissions associated with the application of this manure to cropland also increase with market weight.

The relative contribution to the GWP of pig production from weaned piglets entering the grow-finish decreases over the assessment period from 18 percent to 14 percent of the total. This is attributable to several factors including: increased number of piglets per litter and more efficient feed conversion by sows.

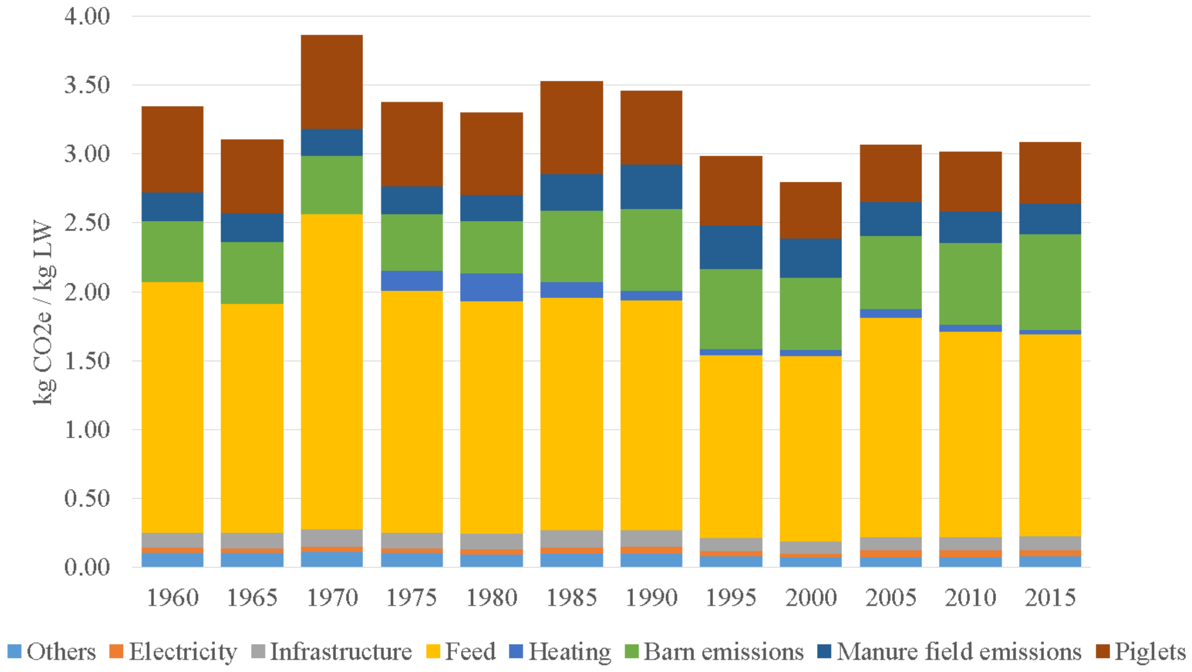

Figure 8. Contribution results for GWP per functional unit.

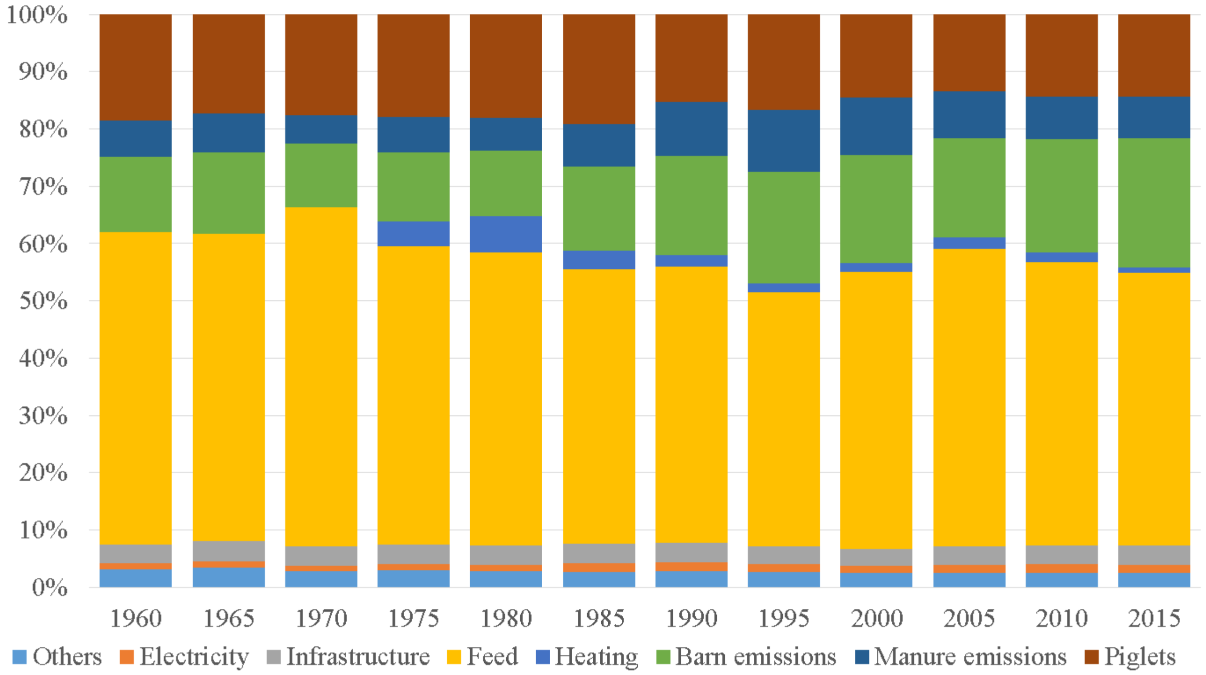

Figure 9. Relative contribution analysis for the national average GWP by major contributors. Impacts included in "others" are from the delivery of municipal water, transport of materials to the farm, and fuel use in the removal and application of manure to fields. Infrastructure refers only to the materials used to construct swine facilities.

3.2 Energy use

With the advent of more enclosed housing beginning in the Southeast in about 1975 (in terms of simulation years), the use of propane for temperature control and animal comfort increased, as shown in Figure 10. The relative contribution of heating to the overall footprint steadily declines as efficiency measures improve over time as shown by the medium dark blue bar. Figure 11 presents the contribution analysis in terms of the functional unit of 1 kg marketed LW; there is a strong correlation with corn production impacts that contribute to the feed impact. The increase beginning in 2005 is associated with introduction of lactose and distillers' grains in swine rations (simulated rations from 2005 onward are based on UA nutritionist recommendations). The increase in energy beginning 2005 is a result of, primarily, drying of lactose and DDGs. This energy is not included in the corn production values shown, thus the correlation of energy use with LW pig stops in 2005.

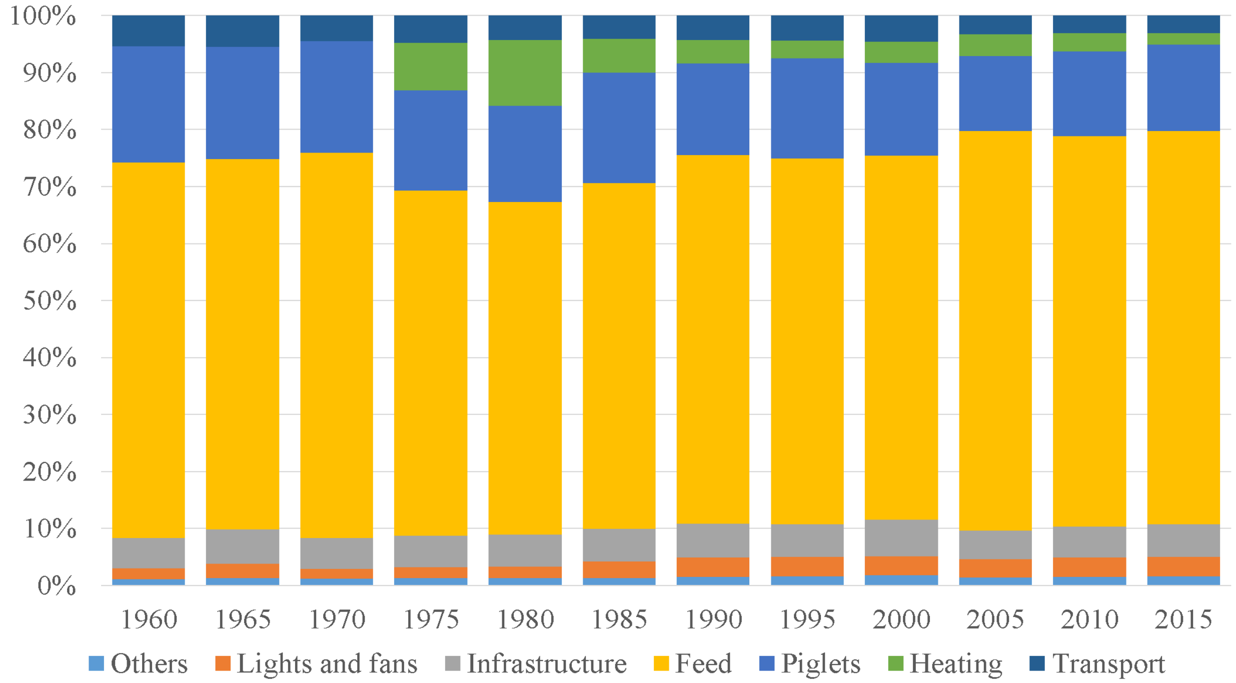

Figure 10. Results are shown for the national average energy use by major contributors. Impacts included in "others" are from the electricity grid, transport of materials to the farm, and other such minor water uses in the upstream supply chain. Infrastructure refers only to the construction materials used to construct swine facilities.

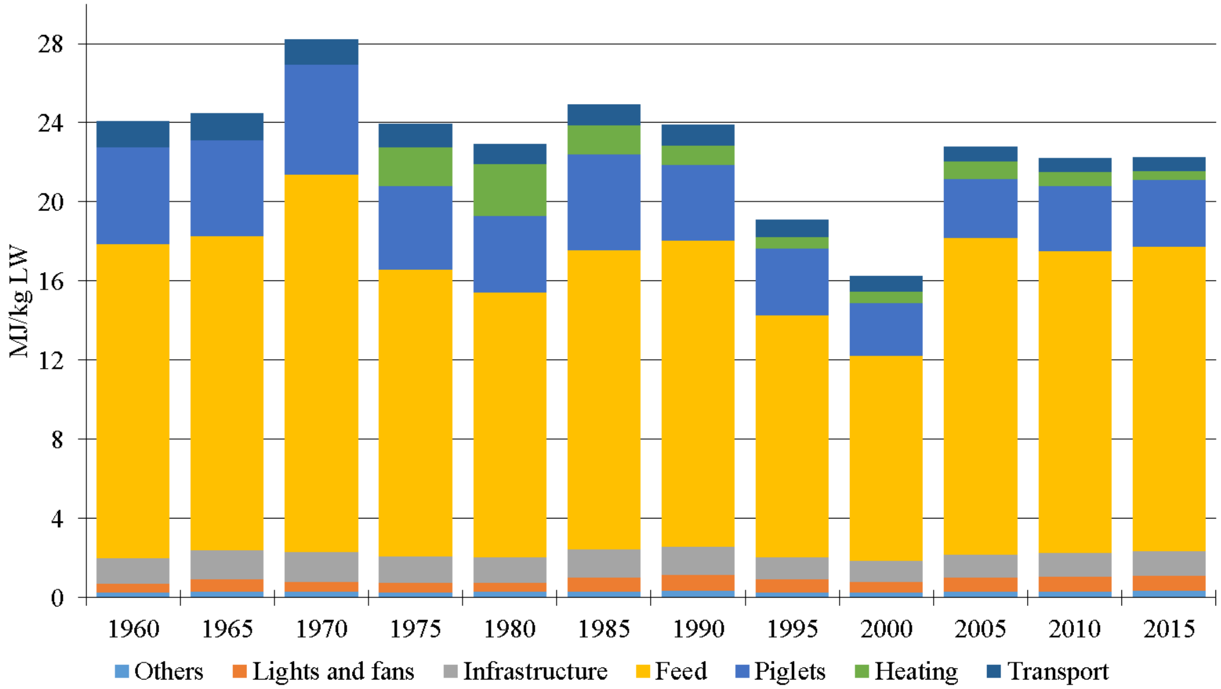

Figure 11. Energy sector contribution to functional unit of 1 kg marketed LW.

3.3 Water use

Water use per kg LW is predominantly driven by irrigation water used in feed production, ranging from 77 to 91 percent of water use, depending on the year. The lack of precipitation in 1970 drove up water use associated with corn as a result of increased irrigation. Irrigation water use in corn and soy production in the United States grew throughout the 1970s and combined with the expansion of heavily irrigated agriculture in Nebraska, water use per kg LW saw little improvement until 1985. Starting around this time, the water use began a consistent decline throughout the next several decades. Figure 12 shows the absolute contribution of different activities; again dominated by production of feed, with a strong correlation to expansion of corn irrigation. The increase in water use beginning in 2005 shown in Figure 12 is largely attributable to the expansion of irrigated acreage, not to the introduction of distillers' grains. The relative increase in cooling water usage, beginning in 1975 in Figure 12 is associated with the advent of modern housing. The relative increase in drinking water over time is attributed to the increase in finishing weights. Since feed consumption is strongly correlated with water

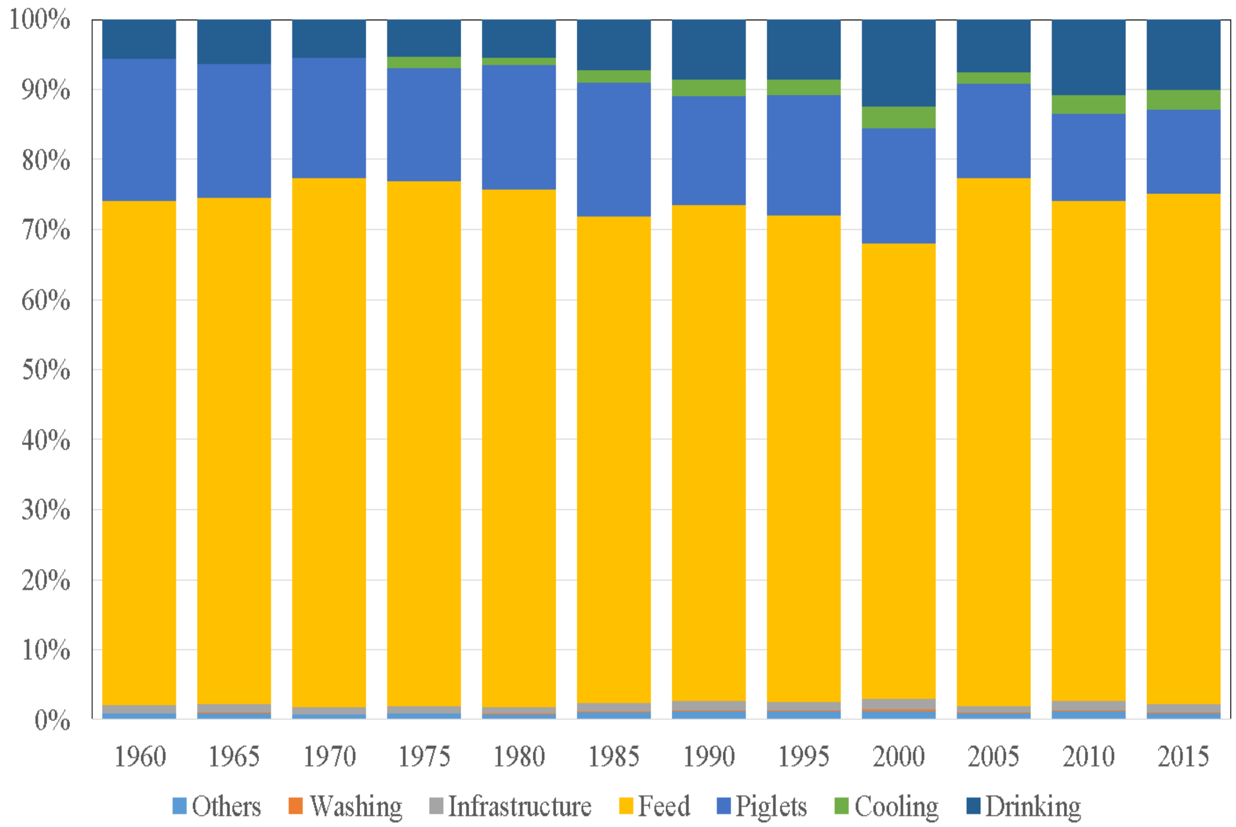

Figure 12. Results are shown for the national average water use major contributors. Impacts included in "others" are from the electricity grid, transport of materials to the farm, and other such minor water uses in the upstream supply chain. Infrastructure refers only to the construction materials used to construct swine facilities.

consumption, and considering feed conversion is less efficient with age, the drinking water associated with a kg LW increases as the finishing weights increase.

3.4 Land use

As mentioned previously, land use is dominated by crop production for the animal ration. This in turn is primarily driven by corn and soy, and to a lesser extent, other ingredients. As discussed in more detail in the next section, there has been a steady and significant improvement in crop yield over the period of the study which is directly responsible for the significant reduction in land occupation associated with swine production. shows the contribution of grow-finish rations and sow rations used for producing the piglets.

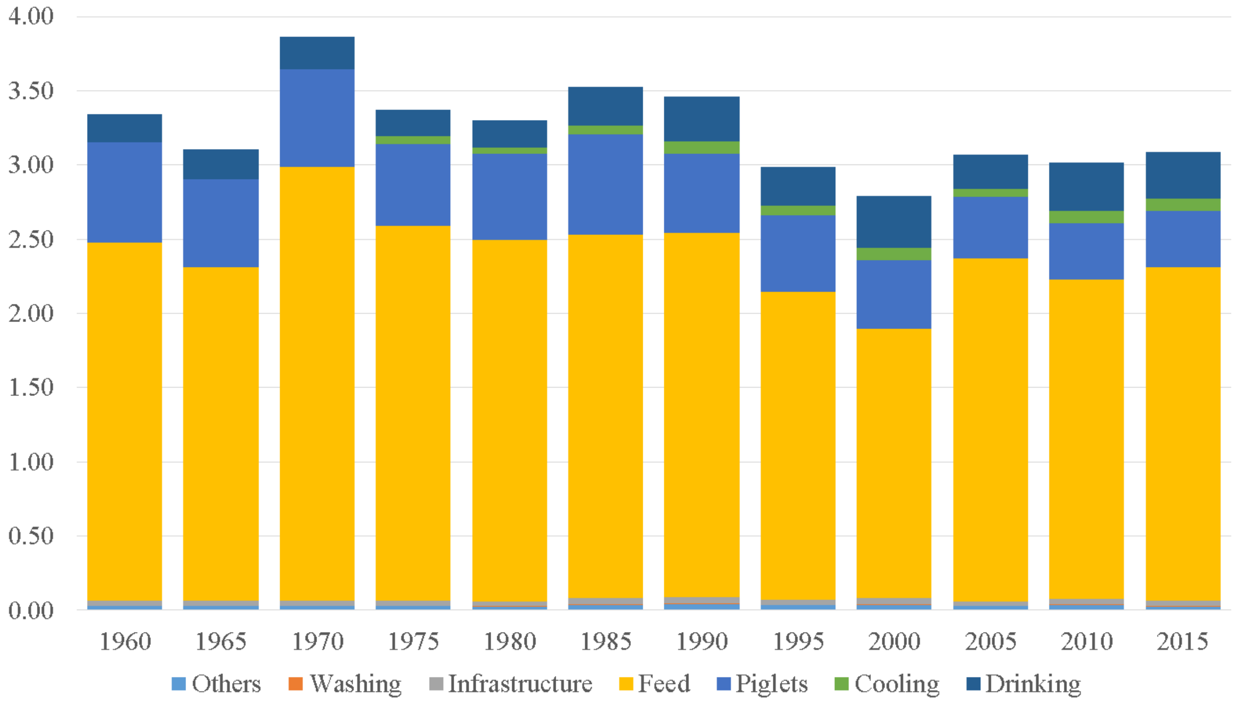

Figure 13. Results are shown for the national average water use major contributors. Impacts included in "others" are from the electricity grid, transport of materials to the farm, and other such minor water uses in the upstream supply chain. Infrastructure refers only to the construction materials used to construct swine facilities.

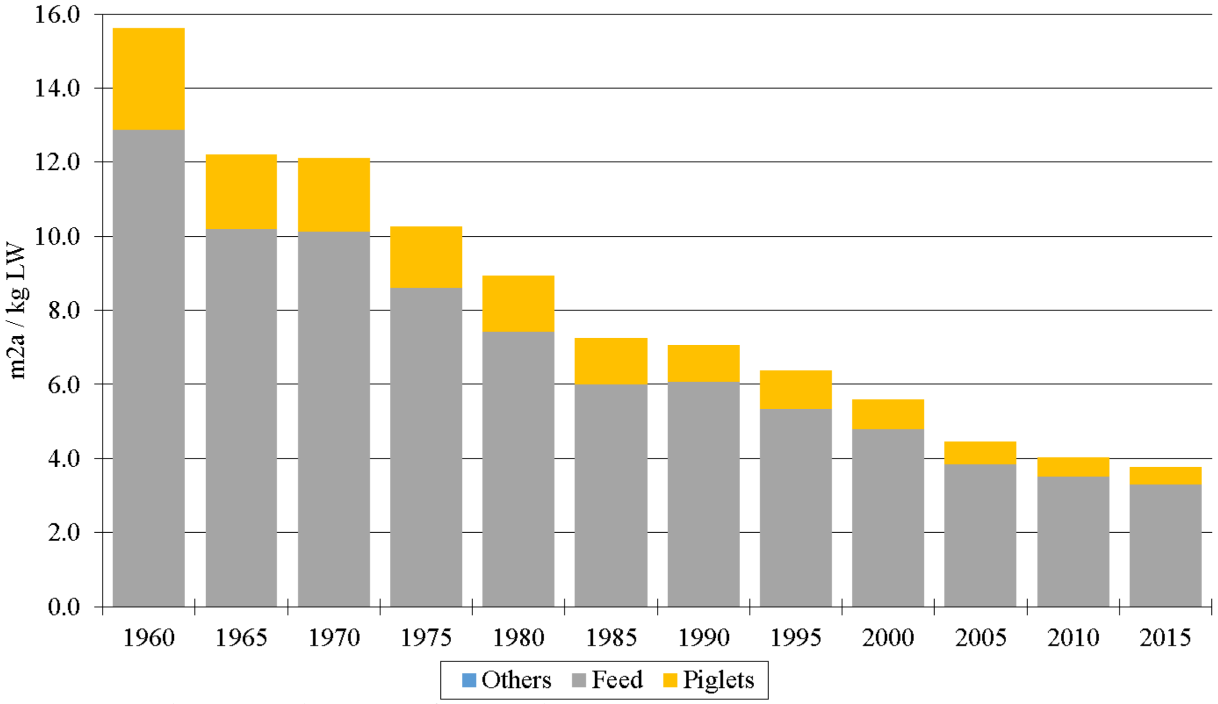

Figure 14. Land use contribution per functional unit.

3.5 Feed

The effects of crop yield on energy use results (Figure 15-D) are similar to that of GWP (Figure 15-C), where the fuel required to plant and harvest an acre of corn remains fairly consistent, so when yields are low the energy use per kg corn moves in tandem with GWP. As mentioned previously, there have been steady, aside from drought years, improvements in the environmental performance of the major crops used in swine rations. This is driven primarily by increased yields, as shown in Figure 15-A where there is steady decline in land occupation (the inverse of yield – corn = blue; soybean = orange). Except

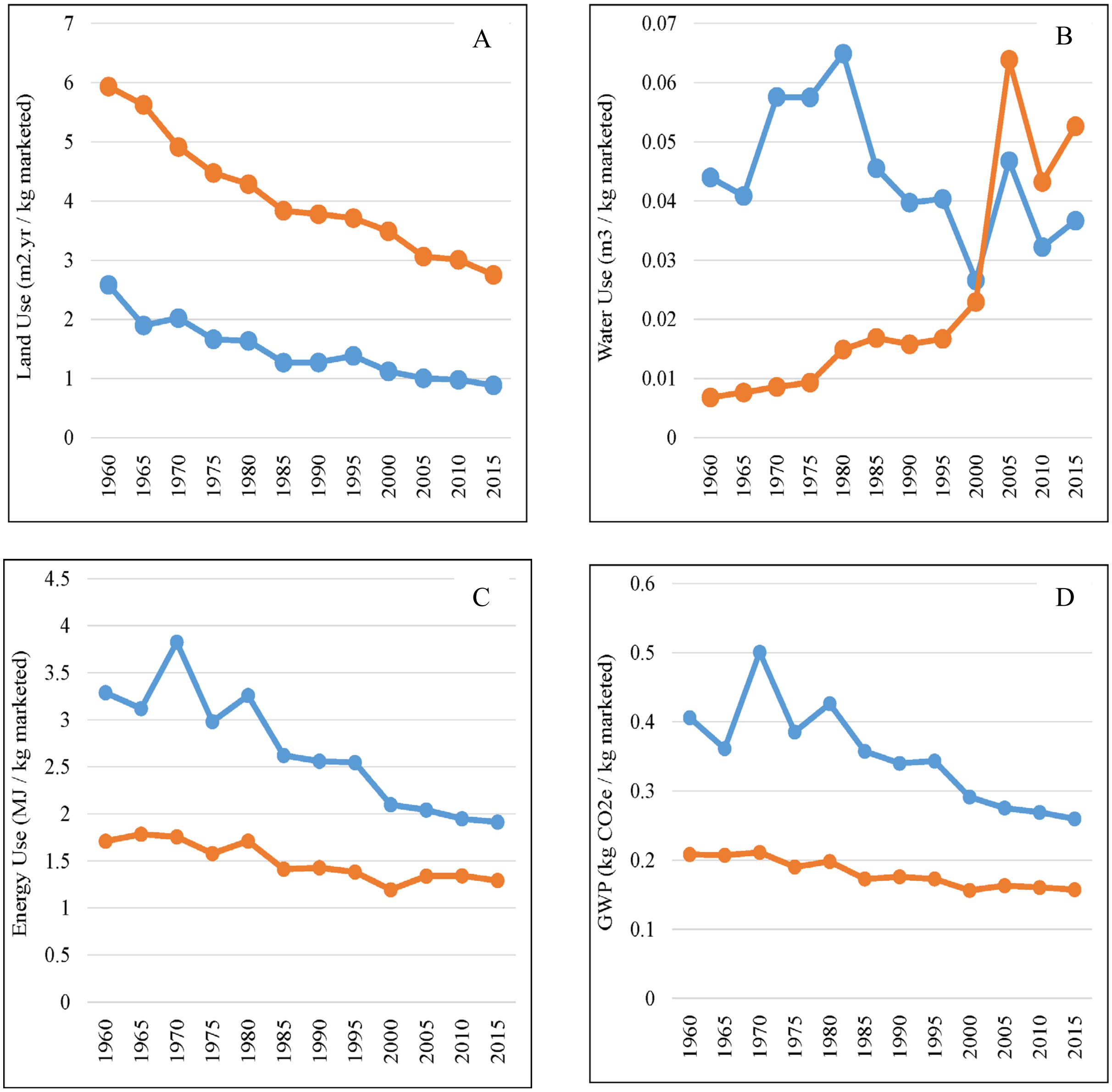

Figure 15. LCIA results for 1kg corn grain and soybean produced, on average, in the U.S. for each simulation year of the assessment. Impact categories are land use (m^2a), water use (m^3), energy use (MJ), and GWP (kg CO_2e).

for water use for soybeans, which has steadily increased primarily because of larger fraction of total acreage under irrigation, both staple feeds show steady declines in environmental impact. This coupled with improved FCR for the animals is a significant source of overall improvement.

Because the ration contributes approximately 50% of the impacts for global warming and energy consumption and 90% or more to the water and land use metrics, we present detailed contribution assessment of different feed ingredients to the impacts of the grow-finish and sow barn rations in the following figures (Figure 16 through Figure 23). These figures are each reporting the contribution assessment of the bar associated with the production of the feed for the grow-finish barn in the figures of the previous section. The feed contribution assessment for the sow barn is associated with the contribution of "piglets" to the corresponding chart in the previous section. The y-axis in each of the figures represents the absolute contribution to the full footprint of production of 1 kg LW at the farm gate, inclusive of cull sows' contribution to the production total. The most striking results are in Figure 16, Figure 17, Figure 20 and Figure 21 where the significant effect of adding lactose and distillers' grains to the diet can be seen. It is noteworthy that the effect of addition of dry lactose (lighter green in the figures) to the rations in 2005, based on nutritionists' recommendations, contributes more significantly to the global warming potential and energy use metrics than the distillers' grains (darker green in the figures).

The land and water use metrics are driven almost entirely by corn and soy production across the full simulation period; there are minor contributions from other activities, but these are generally minor, aside from dry whey, added to the ration in 2005 – 2015.

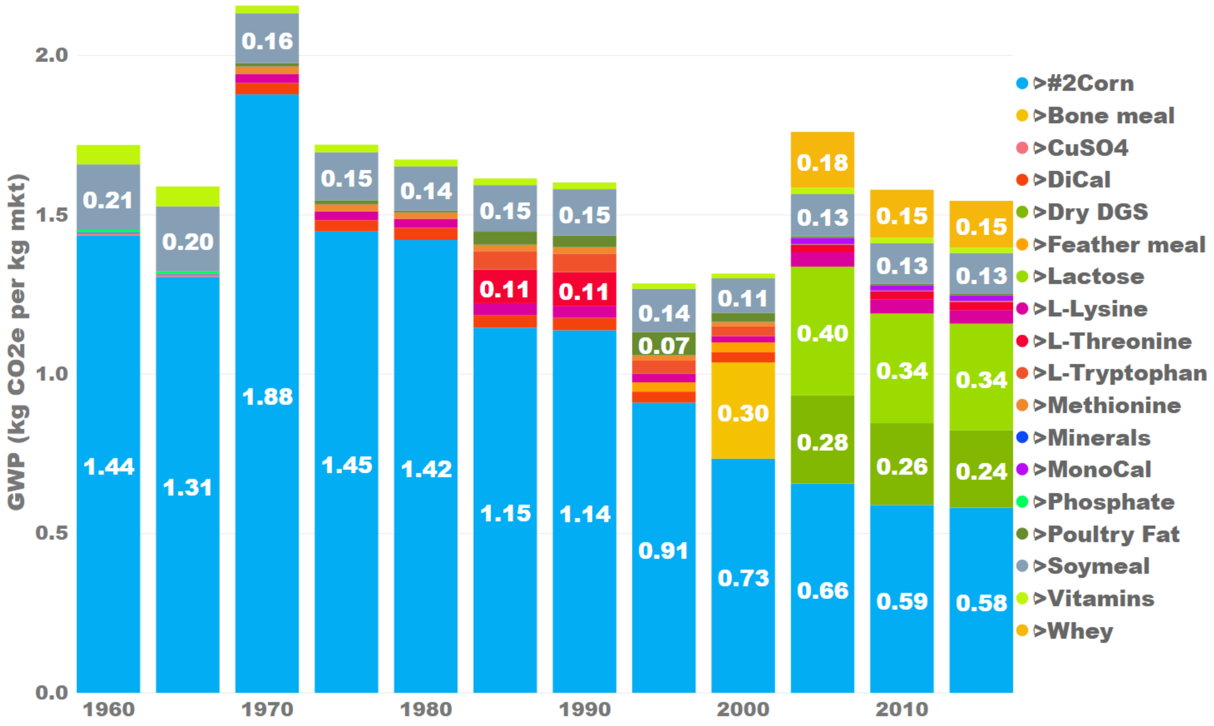

Figure 16. Global warming potential of production the grow-finish barn ration for 1 kg LW marketed.

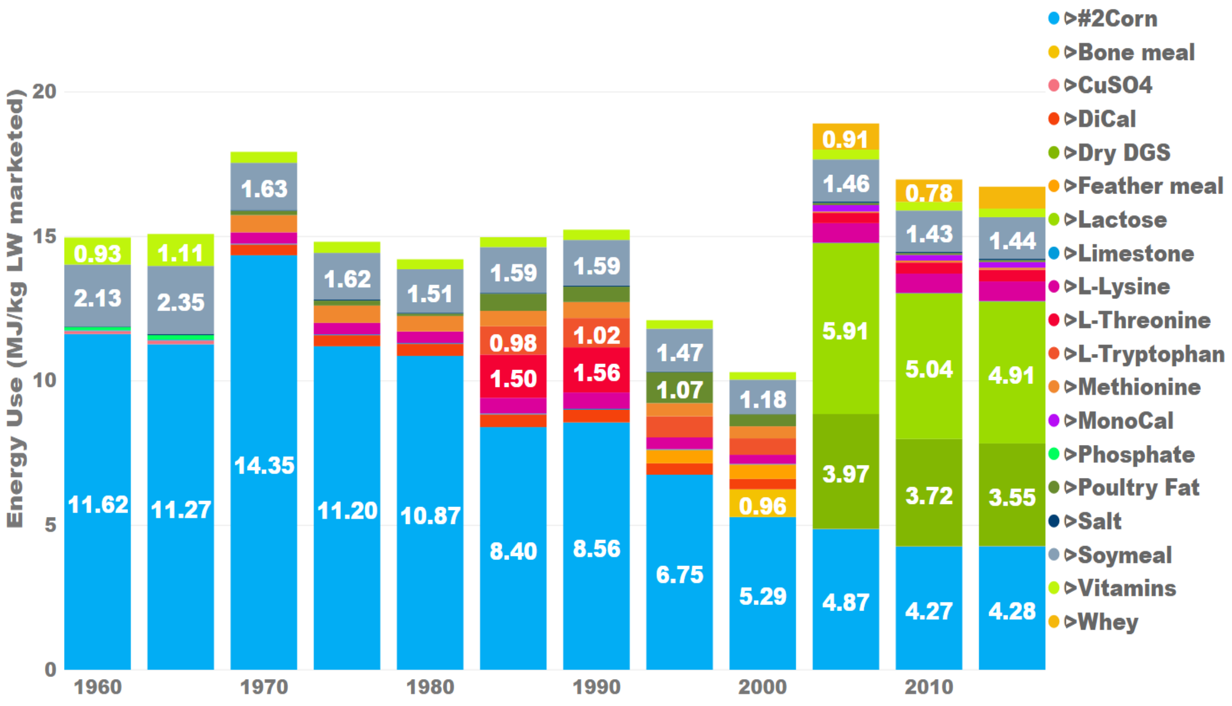

Figure 17. Energy use of production the grow-finish barn ration for 1 kg LW marketed.

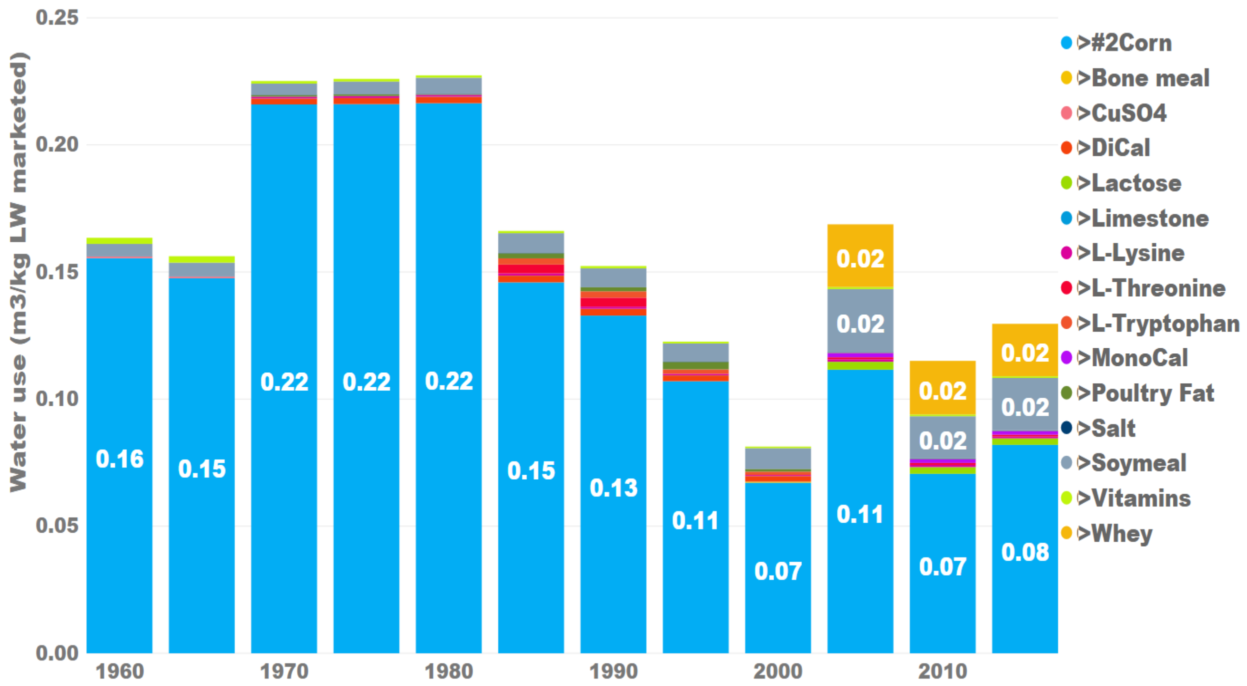

Figure 18. Water use of production the grow-finish barn ration for 1 kg LW marketed.

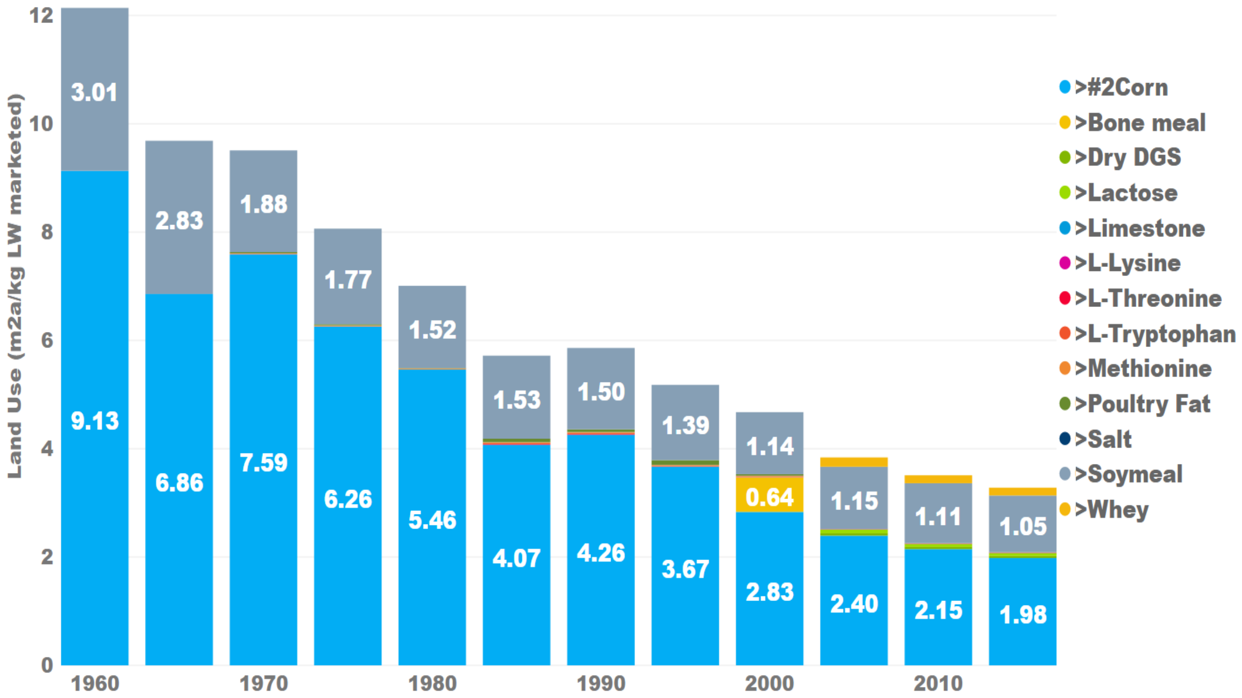

Figure 19. Land use associated with production the grow-finish barn ration for 1 kg LW marketed.

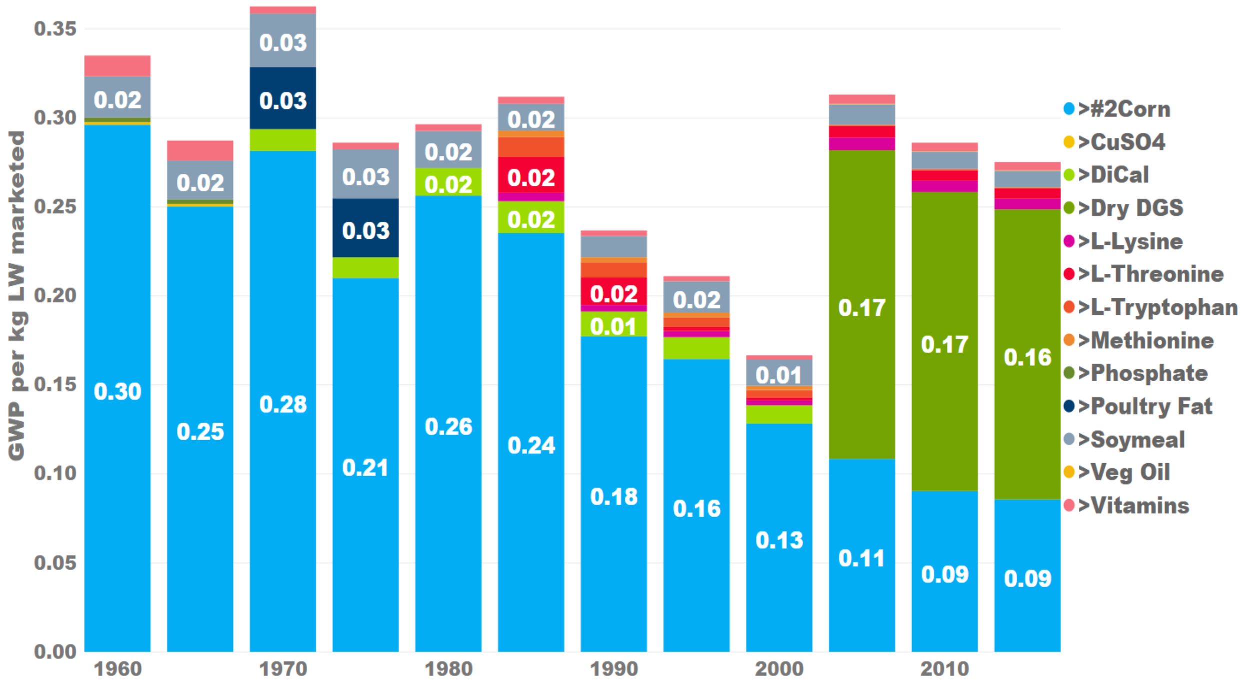

Figure 20. Global warming potential of production the sow barn ration for 1 kg LW marketed.

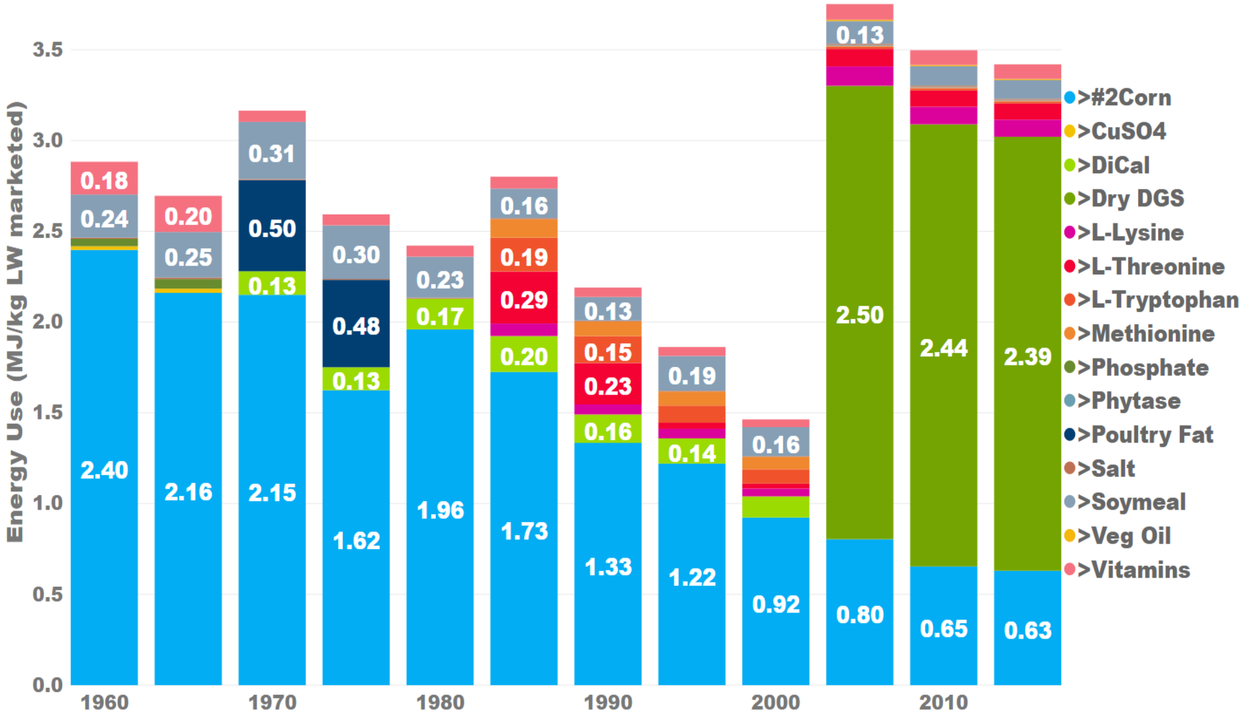

Figure 21. Energy use for production the sow barn ration for 1 kg LW marketed.

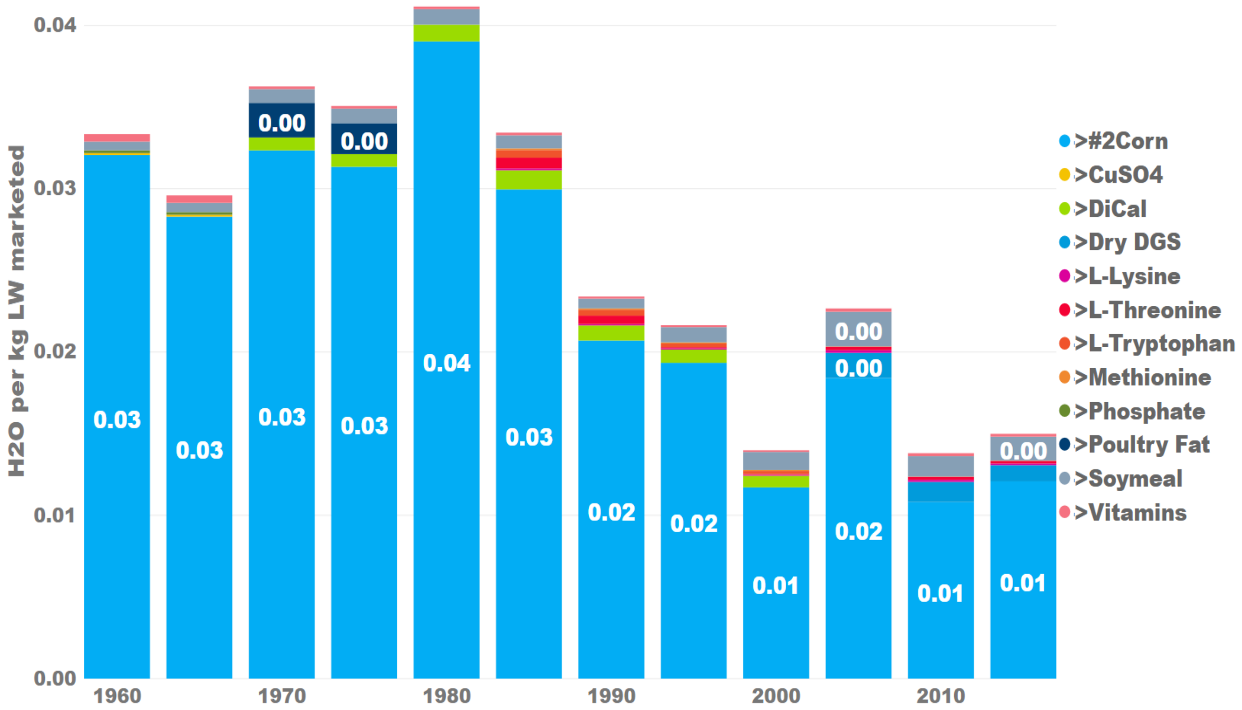

Figure 22. Water use of production the sow barn ration for 1 kg LW marketed.

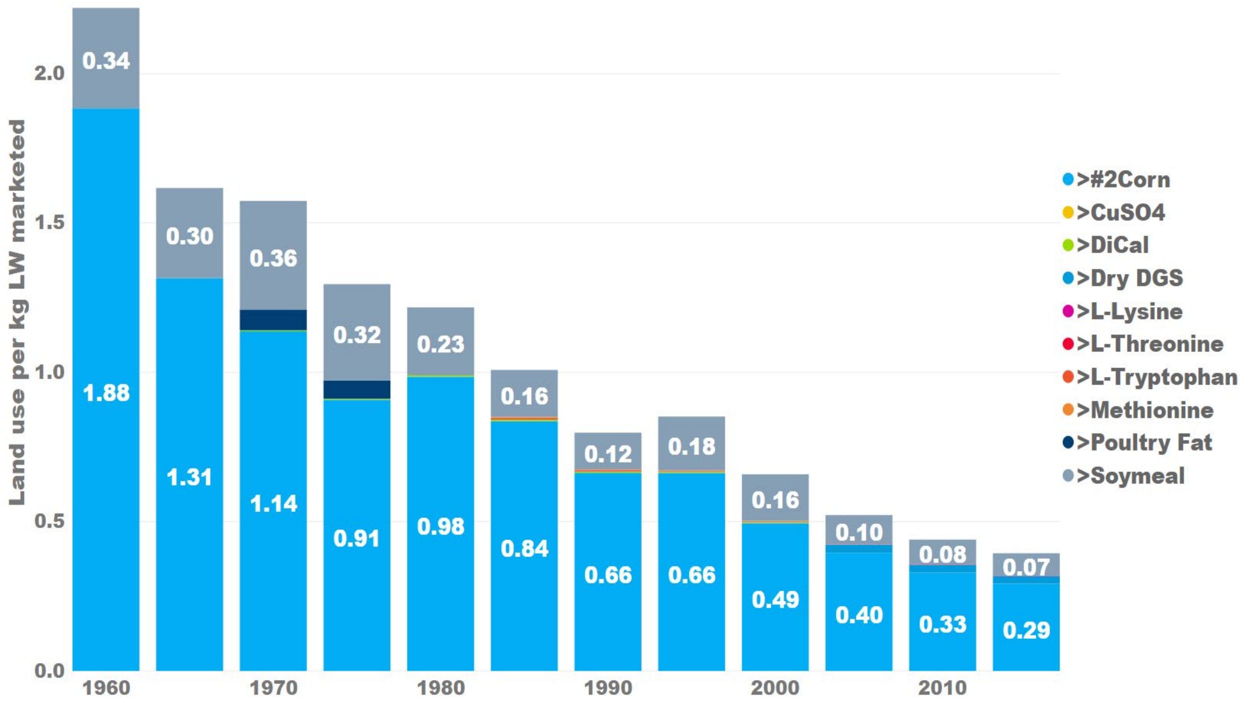

Figure 23. Land use associated with production the sow barn ration for 1 kg LW marketed.

3.6 Background systems

Several background systems were adapted via alterations made to existing USEI unit processes in order represent changes in production efficiency representative of individual simulation years. Overall, these changes had a positive impact on the environmental impacts associated with pig production. This effect is shown in Figure 25, which presents the energy use required to produce 1 kg of nitrogen for the national average mix in each simulation year overlaid with the types of fertilizer constituting the mix in each year, which presents the energy use required to produce 1 kg of nitrogen over time. There are two changes that happen simultaneously between simulation years that are causing the change in energy use: the changing mix of fertilizers used in corn and soy production and the decreasing energy requirements in nitrogen production. Combined, these two changes enable the production of nitrogen fertilizers to improve from 65 MJ/kg N in 1960 to 32 MJ/kg N in 2015.

Another area of improvement in the background systems can be seen in the electricity grid Figure 24. shows the production sources for electricity grid mix in each simulation year alongside the GWP of 1 MJ electricity. Although no changes were made to individual power generation unit processes to represent changing efficiencies, the GWP of producing 1 MJ in the United States declined over the assessment period because of the changing mix of primary energy for electric power generation. The decline in coal-

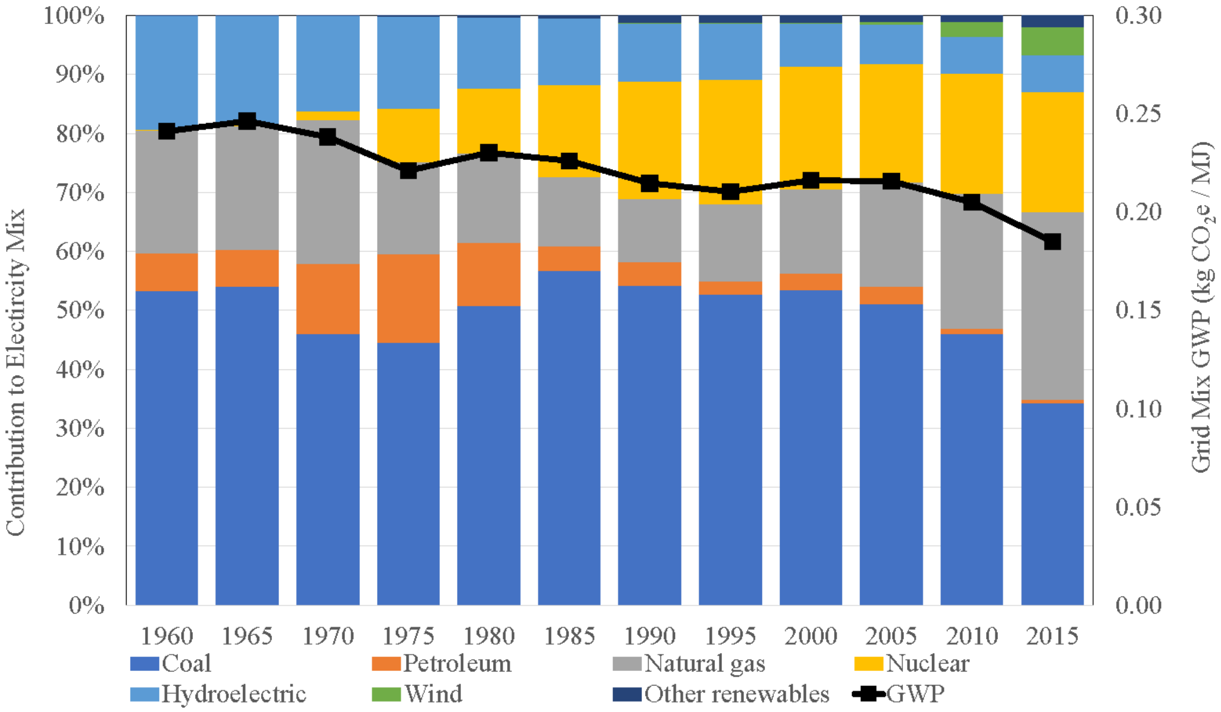

Figure 24. Composition of primary fuel mix for electricity generation and average U.S. electric grid GWP

fired power, in addition to the rise in natural gas and renewables, has resulted in a decline in GWP for electricity production from 0.24 to 0.18 kg CO2e/ MJ over the assessment period. Thus, some of the improvement in swine performance is attributable to improvements in background systems. During the past 55 years, there have been major efforts to improve transportation and manufacturing energy efficiency, as well as shifts away from coal toward natural gas for electric power generation. These improvements were partially incorporated into the lifecycle inventory on a rolling average basis.

3.6.1 Nitrogen fertilizer mix and production

As shown in Figure 25, both the typical mix of nitrogen fertilizers and composition have changed markedly. The 2-fold reduction in energy consumption per kg N fertilizer is due to a combination of manufacturing efficiency as well as a shift to less energy intensive forms.

In addition to the electricity mix and fertilizer production, improvements in transportation and tractor efficiency also played a role in the improvement of domestic live swine production. Improvements in these areas were modeled as linear regressions and as such, their contributions to impacts decline from

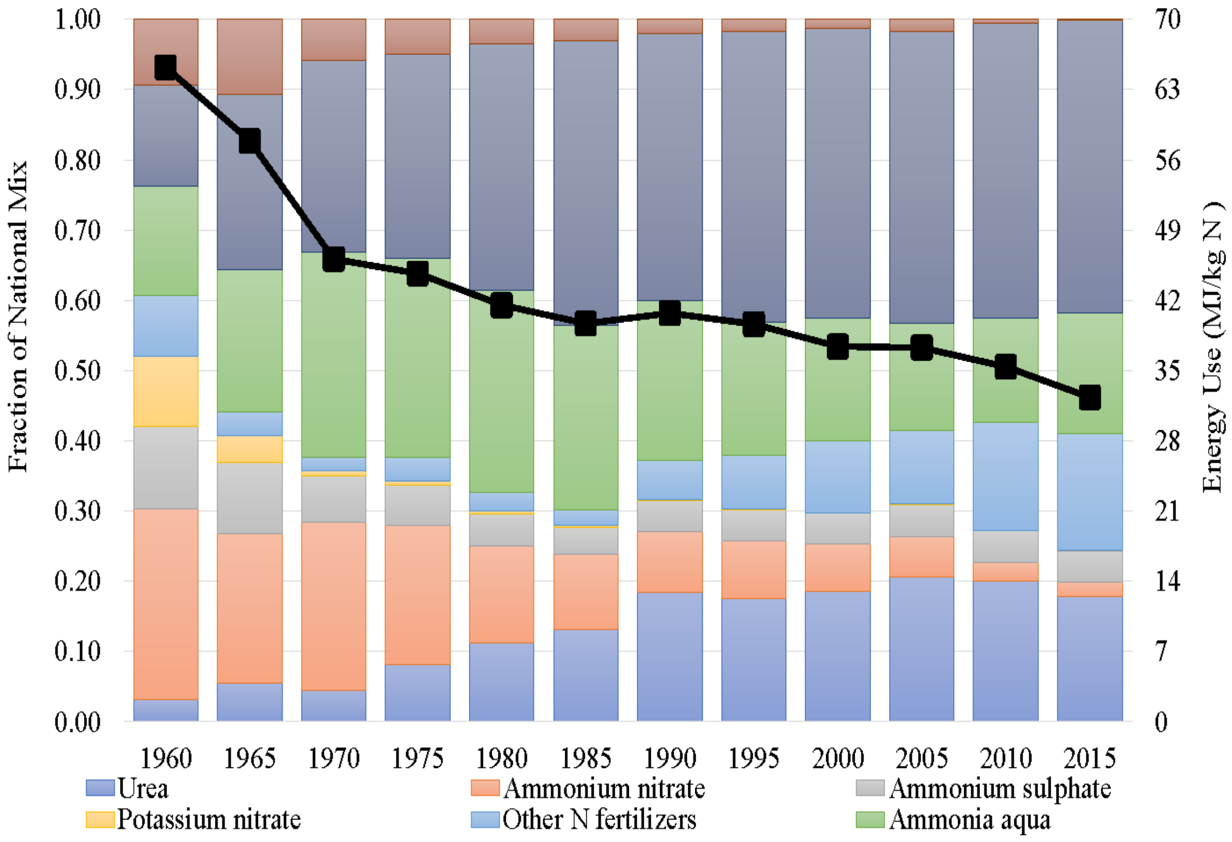

Figure 25. The national consumption mix of nitrogen fertilizer in the U.S. graphed against the energy requirements to produce 1 kg N in each simulation year.

1960 to 2015 relative to their improvement percentages listed in Table 7. While some of these improvements are quite large, such as the 209 percent improvement in ocean transport, their overall contribution to the production of pigs is quite minor.

3.7 National results

Annual pork production increased by 84 percent from 1960 to 2015. The impact intensity (per kg LW) associated with that production has steadily declined (Table 9); however, because of the significant increase in production, three of the cumulative sector impacts have declined (GWP, energy and water), while land use generally decreased (Table 10 and Figure 26). The GWP, water use, and land use results track with sectoral output in production from 1960 to 1985. Cumulative water use breaks this trend in 1990 by declining slightly from 1985 despite an increase in production. By 1995, GWP and energy use also begin declining, despite further increases in annual production. This trend is reversed by 2005, which was the simulation year in which DDGS were added to the rations. The dramatic increase in water use in 2005 is coincidental to the addition of DDGS but is actually driven by higher water use in corn and soybean production. Despite producing nearly twice as much pork in 2015 as in 1960, the total land use associated with live animal production in the pork industry has continually declined. Steady gains in yield of corn and soybeans over this period were further amplified by the improvements in FCR of pigs. As a result, the pork supply chain occupies less than half of the land it did in 1960.

Table 9. Production weighted environmental metrics per kg LW marketed.

Year	Water Use, m3/kg	Land Use, m2a/kg	GWP, kgCO2e/kg	Energy Use, MJ/kg	Production, kg LW
1960	0.241	15.61	3.34	24.17	8.61E+09
1965	0.228	12.20	3.10	24.59	8.27E+09
1970	0.317	12.10	3.86	28.32	9.91E+09
1975	0.317	10.25	3.37	24.05	7.63E+09
1980	0.322	8.92	3.30	23.04	1.06E+10
1985	0.253	7.24	3.52	25.04	9.13E+09
1990	0.223	7.05	3.46	24.05	9.66E+09
1995	0.183	6.36	2.98	19.21	1.11E+10
2000	0.129	5.59	2.79	16.38	1.17E+10
2005	0.226	4.44	3.07	22.93	1.24E+10
2010	0.163	4.02	3.01	22.39	1.37E+10
2015	0.180	3.77	3.08	22.47	1.58E+10

Table 10. Estimated cumulative environmental metrics for the entire production sector, from field-to-farm gate.

Year	Water Use, m3	Land Use, acre	GWP, kgCO2e	Energy Use, MJ	Production, kg LW
1960	2.08E+09	3.32E+07	2.88E+10	2.08E+11	8.61E+09
1965	1.88E+09	2.49E+07	2.56E+10	2.03E+11	8.27E+09
1970	3.14E+09	2.96E+07	3.82E+10	2.81E+11	9.91E+09
1975	2.42E+09	1.93E+07	2.57E+10	1.84E+11	7.63E+09
1980	3.42E+09	2.34E+07	3.50E+10	2.45E+11	1.06E+10
1985	2.31E+09	1.63E+07	3.22E+10	2.29E+11	9.13E+09
1990	2.16E+09	1.68E+07	3.34E+10	2.32E+11	9.66E+09
1995	2.02E+09	1.74E+07	3.30E+10	2.13E+11	1.11E+10
2000	1.51E+09	1.61E+07	3.25E+10	1.91E+11	1.17E+10
2005	2.81E+09	1.36E+07	3.81E+10	2.85E+11	1.24E+10
2010	2.24E+09	1.36E+07	4.14E+10	3.08E+11	1.37E+10
2015	2.85E+09	1.47E+07	4.88E+10	3.55E+11	1.58E+10
actual change	37.4%	-55.7%	69.5%	70.6%	83.6%

Table 10 also shows the sector scale change in the environmental metrics compared to the change that would have occurred if the production intensity had remained constant at 1960 levels (i.e., an 83.6% increase across all metrics, based on the increase in production. Thus without the continual gains in efficiency, total cumulative impacts would be considerably larger today.

4 Conclusions

This assessment of swine production presented a time series evaluation of the environmental sustainability quantified through GHG emissions, energy, water and land use. A significant effort to identify the many factors that were dynamically changing over the past 55 years led to creation of lifecycle inventory data used for simulation of fertilizer, crop and live animal production at five-year increments. The complexity of interactions among the changing parameters (i.e., background transportation and manufacturing efficiency, improved genetics of crops and animals, etc) make it difficult to identify and quantify specific factors driving the improvements observed. Broadly speaking, the adage, “A rising tide lifts all boats,” is apt. Nonetheless, there are some strong correlations that can be identified:

- Land use improvement is driven primarily by the combination of factors leading to improved crop yields
- Water use is also strongly tied to irrigation for crops
- Feed conversion and daily gain contribute to reduction in all categories

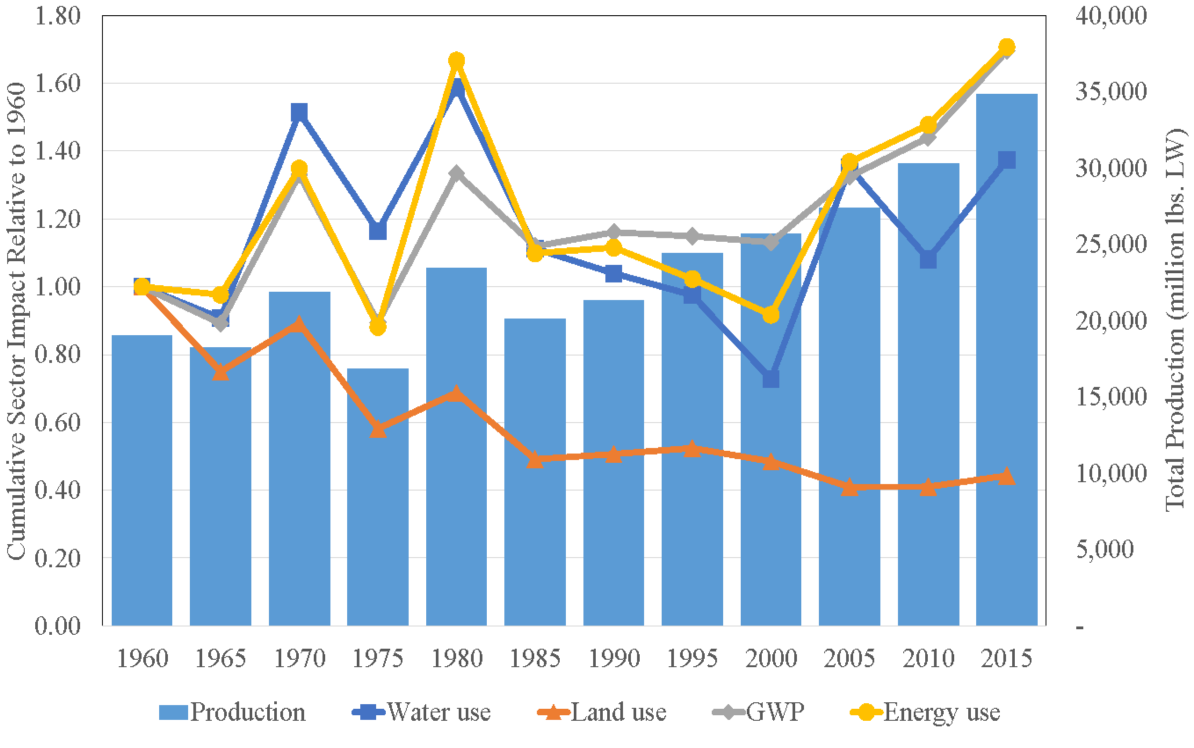

Figure 26. Annual pork production in the U.S. from 1960 to 2015 and the associated impacts. Pork production is shown in millions of pounds of LW pigs and is inclusive of market pigs and cull animals. Environmental impacts are presented in terms of the total industry impact to the farm gate relative to 1960 levels

- The shift in housing beginning in the mid-1970s initially increased energy and greenhouse gas footprints, but efficiencies improved leading to a steady decline; increasing up to about 30MJ/kg LW, and holding steady till 1985 and declining to a low of 17 before the introduction of dried distillers' grains in the early 2000s led to an increase in energy consumption associated with the energy required for drying
- The trend in greenhouse gas emissions is similar to that of energy, but in the 2000s shows a larger variation due to the regional feeding of distillers' grains. GHG emissions decrease from approximately

The United States swine industry has experienced many structural changes over the past 55 years. In addition, there have been continual improvements in the background supply chain supporting swine production. Within the industry, there has been a major shift from extensive to intensive production systems which initially increased environmental burden, but ultimately led to reductions through improved efficiencies: improved daily gain and feed conversion as well as increased fecundity and decreased mortality. There has also been a shift in the manure management practices, partially driven by the intensification of swine production over the period coupled with increased regulation. The environmental impacts per produced animal and kg LW have steadily declined since 1970 - 1980; however, because the total output of the sector has risen dramatically over the same period, there has been a slowly increasing cumulative environmental impact associated with entire sector driven by large growth of the sector output over the period. The sector level impact is estimated by weighted averaging of the simulated counties for each simulation year and aggregating to national production. **It is important to recognize that without the significant gains in reducing the footprint intensity of production that has occurred in the past 55 years, the cumulative environmental impacts for the whole sector would be larger today. If the footprint intensity had remained constant, the sector impacts would have increased in proportion to the increased production: 84%. However, cumulative sector water use only increased by 37.4%; land use *decreased* by 55.7%; and GHG emissions and energy use increased by only 70%.**

5 References

Alhotan, R., Pesti, M.G., 2016. Windows User-Friendly Feed Formulation 2.1. https://doi.org/https://doi.org/10.13140/RG.2.2.17489.53603

Becker, D.E., 1959. Balancing Swine Rations. Urbana, Illinois.

Bond, T.., Peterson, G.., 1958. Hog Houses. Washington, DC.

Carlisle, G.R., Russell, H.G., 1970. Your Hog Business: Ration Suggestions. Urbana, Illinois.

CME Group, 2012. CBOT Soybeans vs . DCE Soybean Meal and Soybean Oil – Crush Spread [WWW Document]. URL https://goo.gl/CKssF8

Cromwell, D., 2017. Soybean Meal–An Exceptional Protein Source.

Davis, S.C., Diegel, S.W., Robert, B., Boundy, R.G., n.d. Transportation energy data book, Cenetr for Transportation Analysis Energy and Transportation Science Division.

Fernandez-Cornejo, J., Vialou, A., 2014. Pesticide Use in U. S. Agriculture: 21 Selected Crops, 1960-2008, USDA Economic Information Bulletin. https://doi.org/10.2139/ssrn.2502986

Frischknecht, R., Editors, N.J., Althaus, H., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Köllner, T., Loerincik, Y., Margni, M., 2007. Implementation of Life Cycle Impact Assessment Methods, American Midland Naturalist.

Frischknecht, R., Jungbluth, N., Althaus, H.J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2005. The ecoinvent database: Overview and methodological framework. Int. J. Life Cycle Assess. 10, 3–9. https://doi.org/10.1065/lca2004.10.181.1

Gottschalk, A., 2007. The impacts of the U.S. corn/ethanol policy on the U.S. cattle industry. Proc. Range Beef Cow Symp. XX.

Hoffman, L. a, Baker, A., 2011. Estimating the Substitution of Distillers ' Grains for Corn and Soybean Meal in the U . S . Feed Complex 1–62.

Hoy, R.M., Rohrer, R., Liska, A., Luck, J.D., Isom, L., Keshwani, D.R., 2014. Agricultural Industry Advanced Vehicle Technology: Benchmark Study for Reduction in Petroleum Use.

Hurley, R., Mcpike, J.D., 1959. Statistics By Subiects.

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., Maupin, M.A., 2004. Estimated Use of Water in the United States in 2000, U.S. Geological Survey Circular 1268.

IFA, 2009. Energy Efficiency and CO2 Emissions in Ammonia Production 2008-2009 Summary Report. Paris, France.

Intergovernmental Panel on Climate Change, 2006. N2O Emissions From Managed Soils, and CO2 Emissions From Lime and Urea application. 2006 IPCC Guidel. Natl. Greenh. Gas Invent. Vol. 4

Agric. For. Other L. Use 11.1-11.54.

Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., Maupin, M. a, 2009. Estimated Use of Water in the United States in 2005 Circular 1344, Water. https://doi.org/http://dx.doi.org/10.3133/cir1405

MacKichan, K.A., Kammerer, J.C., 1960. Estimated Use of Water in the United States in 1960, U.S. Geological Survey Circular 456. Washington, DC.

Maupin, M.A., Kenny, J.F., Hutson, S.S., 2014. Estimated Use of Water in the United States in 2010 Circular 1405, US Geological Survey. https://doi.org/10.3133/cir1405

Murray, C.R., 1968. Estimated Use of Water in the United States in 1965.

Murray, C.R., Reeves, E.B., 1977. Estimated Use of Water in the United States in 1975, U.S. Geological Survey Circular 765. Washington, DC.

Murray, C.R., Reeves, E.B., 1975. Estimated Use of Water in the United States in 1970, U.S. Geological Survey Circular 676. Washington, DC.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and Natural Radiative Forcing. Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang. 659–740. https://doi.org/10.1017/CBO9781107415324.018

National Research Council, 2012. Nutrient Requirements of Swine. https://doi.org/10.17226/13298

National Research Council, 1998. Nutrient Requirements of Swine. The National Academies Press, Washington, DC. https://doi.org/10.17226/6016

National Research Council, 1988. Nutrient Requirements of Swine, 4th ed. The National Academies Press, Washington, DC.

National Research Council, 1979. Nutrient Requirements of Swine, 3rd ed. The National Academies Press, Washington, DC. https://doi.org/10.17226/19882

National Research Council, 1973. Nutrient Requirements of Swine, 2nd ed. The National Academies Press, Washington, DC.

NCDC, 2015. Climate Data Online (CDO) | National Climatic Data Center (NCDC) [WWW Document]. URL http://www.ncdc.noaa.gov/cdo-web/#t=firstTabLink

Nene, G., Azzam, A.M., Schoengold, K., 2009. Environmental Regulations and the Structure of U.S. Hog Farms, in: Agricultural & Applied Economics Association 2009 AAEA & ACCI Joint Annual Meeting. pp. 1–29.

Putman, B., Thoma, G.J., Burek, J., Matlock, M.D., 2017. A retrospective analysis of the United States poultry industry: 1965 compared with 2010. Agric. Syst. 157, 107–117. https://doi.org/10.1016/j.agsy.2017.07.008

RFA, 2018a. Industry Statistics – Renewable Fuels Association [WWW Document].

RFA, 2018b. Ethanol Biorefinery Locations – Renewable Fuels Association [WWW Document].

Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.K., Bloom, S., Chen, J., Collins, D., Conaty, A., Da Silva, A., Gu, W., Joiner, J., Koster, R.D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C.R., Reichle, R., Robertson, F.R., Ruddick, A.G., Sienkiewicz, M., Woollen, J., 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. J. Clim. 24, 3624–3648. https://doi.org/10.1175/JCLI-D-11-00015.1

Safranski, T., 2005. Management of Replacement Gilts. Present. P.O.R.K. Acad. Des Moines, IA.

Shapouri, H., Mathews, K.H., Bailey, P., 1988. Costs and Structure of U. S. Hog Production.

Solley, W.B., Chase, E.B., Mann IV, W.B., 1985. Estimated Use of Water in the United States in 1980, U.S. Geological Survey Circular 1001. Washington, DC.

Solley, W.B., Merk, C.F., Pierce, R.R., 1988. Estimated use of water in the United States in 1985. U.S. Geol. Surv.

Solley, W.B., Pierce, R.R., Perlman, H. a., 1993. Estimated Use of Water in the United States in 1990: U.S. Geological Survey Circular 1081. U.S. Geol. Surv. 86.

Solley, W.B., Pierce, R.R., Perlman, H.A., 1998. Estimated Use of Water in the United States in 1995, USGS Science for a changing world. https://doi.org/10.2172/887320

Stein, H.H., Shurson, G.C., 2009. Board-invited review: the use and application of distillers dried grains with solubles in swine diets. J. Anim. Sci. 87, 1292–303. https://doi.org/10.2527/jas.2008-1290

US EIA, 2014. Monthly Energy Report. Washington, DC.

USDA, 2014. Farm and Ranch Irrigation Survey (2013). 2012 Census Agric. 3, 216.

USDA, 2009. 2007 Census of Agriculture. Washington, DC.

USDA, 2008. Swine 2006: Part IV: Changes in the U.S. Pork Industry, 1990-2006, Management. Fort Collins, CO.

USDA, 2004. 2002 Census of Agriculture. Washington, DC.

USDA, 1999. 1997 Census of Agriculture. Washington, DC.

USDA, 1996. 1992 Census of Agriculture. Washington, DC.

USDA, 1989. 1987 Census of Agriculture. Washington, DC.

USDA, 1984. 1982 Census of Agriculture. Washington, DC. https://doi.org/10.5962/bhl.title.18473

USDA, 1981. 1978 Census of Agriculture. Washington, DC. https://doi.org/10.1111/j.1475-

6765.2009.01870.x

USDA, 1978. 1974 Census of Agriculture. Washington, DC.

USDA, 1973. 1969 Census of Agriculture. Washington. https://doi.org/10.1117/12.814049

USDA, 1967. 1964 Census of Agriculture. Washington, DC.

USDA ERS, 2018a. Feed Grains Database [WWW Document]. Feed Grains Cust. Query.

USDA ERS, 2018b. Fertilizer use and markets [WWW Document]. Dataset.

USDA NASS, 2018. USDA/NASS QuickStats Ad-hoc Query Tool [WWW Document].

Van Arsdall, N.R., 1978. Structural Characteristics of the US Hog Production Industry.

White, A.M., 1983. I . u . s . s . 4,679,063.

Wisner, R., 2010. Distillers grain price relationships and export developments. AgMRC Renew. Energy Clim. Chang. Newsl.

6 Appendix

6.1 PPEFC input parameters

Appendix Table 1. PPEFC grow-finish barn input parameters

	1960	1965	1970	1975		
Variable	**All states**	**All states**	**All states**	**Southeast**	**North Central**	**Southwest**
What is their weight when they enter	13	13	13	13	13	13
What is their weight when they leave	200	210	220	222	232	227
Roof height	10	10	10	10	10	10
Max allowable approach to outside temp	0	0	0	6	0	0
R value of walls	0	0	0	10	0	0
R value of roof	0	0	0	10	0	0
Fan throughput	0	0	0	22000	0	0
Fan Max Throughput 2	0	0	0	12000	0	0
Fan Max Throughput 3	0	0	0	12000	0	0
Fan power	0	0	0	746	0	0
Fan Power 2	0	0	0	373	0	0
Fan Power 3	0	0	0	373	0	0
Outside temp to start cooling cells	0	0	0	0	0	0
Outside temp to start sprinklers	0	0	0	86	0	0
Hours per day lights are on	0	0	0	5	0	0
Heater BTU per hr per hd	0	0	0	900	0	0
Manually set ADG value	1.45	1.45	1.22	1.22	1.28	1.27
Manually set FCR value	4.32	4.32	4.15	4.15	4.43	4.17
ME_adjustement_factor	2.2	2.1	1.7	1.7	2	1.9
max_protein_dep_adjustment_factor	0.02	0.02	0.06	0.07	0.01	0.05
Mortality rate in grow-finish barn %	1.8	1.8	1.8	2.2	1.5	2.4
Days for cleanup between groups	5	5	5	`	5	5
Number of fans of type 1	0	0	0	25	0	0
Number of fans of type 2	0	0	0	20	0	0
Number of fans of type 3	0	0	0	20	0	0
first day of phase 1	1	1	1	1	1	1
first day of phase 2	19	19	61	61	50	59
first day of phase 3	39	39	107	107	87	102
first day of phase 4	64	64	0	0	0	0
Barn Temperature Control	open	open	open	drop curtain	open	open
Do you use cooling cells	no	no	no	no	no	no
Do you use water drip or sprinkle	no	no	no	sprinkler	no	no
Heating source for barn	none	none	none	propane	none	none
Pig space cu ft per pig	14	12	12	12	12	12

Appendix Table 1 continued.

	1980		1985		1990
Variable	**Southeast**	**North Central**	**Southeast**	**North Central**	**All states**
What is their weight when they enter	13	13	13	13	13
What is their weight when they leave	220	227	220	227	249
Roof height	10	10	10	10	10
Max allowable approach to outside temp	6	0	6	6	6
R value of walls	10	0	20	10	20
R value of roof	10	0	20	10	20
Fan throughput	22000	0	22000	22000	22000
Fan Max Throughput 2	12000	0	12000	12000	12000
Fan Max Throughput 3	12000	0	12000	12000	12000
Fan power	746	0	746	746	746
Fan Power 2	373	0	373	373	373
Fan Power 3	373	0	373	373	373
Outside temp to start cooling cells	0	0	0	0	0
Outside temp to start sprinklers	86	0	86	86	86
Hours per day lights are on	5	0	5	5	5
Heater BTU per hr per hd	900	0	900	900	900
Manually set ADG value	1.29	1.42	1.3	1.3	1.31
Manually set FCR value	3.84	3.68	3.8	3.8	3.83
ME_adjustement_factor	1.5	1.6	1.6	1.6	1.6
max_protein_dep_adjustment_factor	0.2	0.22	0.2	0.2	0.2
Mortality rate in grow-finish barn %	2.2	1.5	1.8	1.8	2.1
Days for cleanup between groups	5	5	5	5	5
Number of fans of type 1	25	0	25	25	25
Number of fans of type 2	20	0	20	20	20
Number of fans of type 3	20	0	20	20	20
first day of phase 1	1	1	1	1	1
first day of phase 2	58	53	83	83	82
first day of phase 3	101	92	0	0	0
first day of phase 4	0	0	0	0	0
Barn Temperature Control	drop curtain	open	tunnel vent	tunnel vent	tunnel vent
Do you use cooling cells	no	no	no	no	no
Do you use water drip or sprinkle	sprinkler	no	sprinkler	sprinkler	sprinkler
Heating source for barn	propane	none	propane	propane	propane
Pig space cu ft per pig	9	8	8	8	8

Appendix Table 1 continued.

Variable	**1995** **All states**	**2000** **All states**	**2005** **All states**	**2010** **All states**	**2015** **All states**
What is their weight when they enter	13	13	13	13	13
What is their weight when they leave	256	262	269	268.7	281.2
Roof height	10	10	10	10	10
Max allowable approach to outside temp	6	6	6	6	6
R value of walls	20	20	20	20	20
R value of roof	20	20	20	20	20
Fan throughput	22000	22000	22000	22000	22000
Fan Max Throughput 2	12000	12000	12000	12000	12000
Fan Max Throughput 3	12000	12000	12000	12000	12000
Fan power	746	746	746	746	746
Fan Power 2	373	373	373	373	373
Fan Power 3	373	373	373	373	373
Outside temp to start cooling cells	0	0	0	0	0
Outside temp to start sprinklers	86	86	86	86	86
Hours per day lights are on	5	5	5	5	5
Heater BTU per hr per hd	900	900	900	900	900
Manually set ADG value	1.7	1.69	1.6	1.5	1.61
Manually set FCR value	3.23	3.03	2.82	2.6	2.58
ME_adjustement_factor	1.7	1.55	1.35	1.25	1.25
max_protein_dep_adjustment_factor	0.43	0.555	0.65	0.75	0.75
Mortality rate in grow-finish barn %	2.2	2.75	1.8	4.41	8.34
Days for cleanup between groups	5	5	5	5	5
Number of fans of type 1	25	25	25	25	25
Number of fans of type 2	20	20	20	20	20
Number of fans of type 3	20	20	20	20	20
first day of phase 1	1	1	1	1	1
first day of phase 2	64	64	68	72	67
first day of phase 3	102	103	109	109	101
first day of phase 4	0	0	0	146	136
Barn Temperature Control	tunnel vent	tunnel vent	tunnel vent	tunnel vent	tunnel vent
Do you use cooling cells	no	no	no	no	no
Do you use water drip or sprinkle	sprinkler	sprinkler	sprinkler	sprinkler	sprinkler
Heating source for barn	propane	propane	propane	propane	propane
Pig space cu ft per pig	8	8	8	8	8

Appendix Table 2. PPEFC sow barn input parameters.

	1960	**1965**	**1970**	**1975**		
Variable	**All states**	**All states**	**All states**	**Southeast**	**North Central**	**Southwest**
Delivery distance for gilts	100	100	100	100	100	100
Piglets surviving to weaning	7	7.2	7.3	7.6	7.2	7.6
Piglets deaths before weaning	3	2.9	2.5	1.6	1.4	1.6
Roof height	10	10	10	10	10	10
Max target temperature in barn	0	0	0	80	80	80
Min target temperature in barn	0	0	0	60	60	60
Max approach to outside temp	0	0	0	6	6	6
R value of walls	0	0	0	20	10	20
R value of roof	0	0	0	20	10	20
Fan throughput	0	0	0	22000	22000	22000
Fan Max Throughput 2	0	0	0	12000	12000	12000
Fan Max Throughput 3	0	0	0	12000	12000	12000
Fan power	0	0	0	746	746	746
Fan Power 2	0	0	0	373	373	373
Fan Power 3	0	0	0	373	373	373
Outside temp for cooling cells	0	0	0	85	85	85
Outside temp for sprinklers	0	0	0	0	0	0
Hours per day lights are on	0	0	0	15	15	15
Heater BTU per hr per hd	0	0	0	3500	3500	3500
Days between delivery of gilts	7	7	7	7	7	7
Average age of incoming gilts	120	180	120	120	120	120
Days between sow culling	6	6	6	6	6	6
Age piglets removed	21	21	21	21	21	21
Weaning to insemination	16	16	16	16	16	16
Days of piglet heater use	5	5	5	5	5	5
Number of fans of type 1	0	0	0	25	25	25
Number of fans of type 2	0	0	0	20	20	20
Number of fans of type 3	0	0	0	20	20	20
Gilt replacement rate %	50	50	50	50	50	50
Sows culled %	47	47	47	47	47	47
Barn Temperature Control	open	open	open	tunnel vent	drop curtain	tunnel vent
Cooling cells	no	no	no	no	no	no
Water drip or sprinkle	no	no	no	no	no	no
Do you use piglet heaters	heat lamps	heat lamps	heat lamps	heat lamps	heat lamps	heat lamps
Heating source for barn	none	none	none	none	propane	propane
Pig space cu ft per pig	40	24	24	24	24	24

Appendix Table 2 continued.

	1980		1985		1990	1995
Variable	**Southeast**	**North Central**	**Southeast**	**North Central**	**All states**	**All states**
Delivery distance for gilts	100	100	100	100	100	100
Piglets surviving to weaning	7.6	7.4	7.3	7.2	8.37	8.49
Piglets deaths before weaning	1.6	2.8	2.4	1.4	1.97	1.53
Roof height	10	10	10	10	10	10
Max target temperature in barn	80	80	80	80	80	80
Min target temperature in barn	60	60	60	60	60	60
Max approach to outside temp	6	6	6	6	6	6
R value of walls	20	10	10	10	20	20
R value of roof	20	10	10	10	20	20
Fan throughput	22000	22000	22000	22000	22000	22000
Fan Max Throughput 2	12000	12000	12000	12000	12000	12000
Fan Max Throughput 3	12000	12000	12000	12000	12000	12000
Fan power	746	746	746	746	746	746
Fan Power 2	373	373	373	373	373	373
Fan Power 3	373	373	373	373	373	373
Outside temp for cooling cells	85	85	85	85	85	85
Outside temp for sprinklers	0	0	0	0	0	0
Hours per day lights are on	15	15	15	15	15	15
Heater BTU per hr per hd	3500	3500	3500	3500	3500	3500
Days between delivery of gilts	7	7	7	7	7	7
Average age of incoming gilts	120	120	120	120	120	120
Days between sow culling	6	6	6	6	6	6
Age piglets removed	21	36	21	21	29	26
Weaning to insemination	16	16	16	16	16	16
Days of piglet heater use	5	5	5	5	5	5
Number of fans of type 1	25	25	25	25	25	25
Number of fans of type 2	20	20	20	20	20	20
Number of fans of type 3	20	20	20	20	20	20
Gilt replacement rate %	50	50	50	50	50	50
Sow culled %	44	44	44	44	44	41
Barn Temperature Control	tunnel vent	drop curtain	tunnel vent	drop curtain	tunnel vent	tunnel vent
Cooling cells	no	no	no	no	no	no
Water drip or sprinkle	no	no	no	no	no	no
Do you use piglet heaters	heat lamps	heat lamps	heat lamps	heat lamps	heat lamps	heat lamps
Heating source for barn	none	propane	propane	propane	propane	propane
Pig space cu ft per pig	14	14	14	14	14	14

Appendix Table 2 continued.

Variable	2000 All states	2005 All states	2010 All states	2015 All states
Delivery distance for gilts	100	100	100	100
Piglets surviving to weaning	8.77	9.38	10	10
Piglets deaths before weaning	1.98	2.46	3	3.5
Roof height	10	10	10	10
Max target temperature in barn	80	80	80	80
Min target temperature in barn	60	60	60	60
Max approach to outside temp	6	6	6	6
R value of walls	20	20	20	20
R value of roof	20	20	20	20
Fan throughput	22000	22000	22000	22000
Fan Max Throughput 2	12000	12000	12000	12000
Fan Max Throughput 3	12000	12000	12000	12000
Fan power	746	746	746	746
Fan Power 2	373	373	373	373
Fan Power 3	373	373	373	373
Outside temp for cooling cells	85	85	85	85
Outside temp for sprinklers	0	0	0	0
Hours per day lights are on	15	15	15	15
Heater BTU per hr per hd	3500	3500	3500	3500
Days between delivery of gilts	7	7	7	7
Average age of incoming gilts	120	120	120	120
Days between sow culling	6	6	6	6
Age piglets removed	19	19	21	22
Weaning to insemination	16	16	16	16
Days of piglet heater use	5	5	5	5
Number of fans of type 1	25	25	25	25
Number of fans of type 2	20	20	20	20
Number of fans of type 3	20	20	20	20
Gilt replacement rate %	50	50	50	50
Sow culled %	38	49	47	47
Barn Temperature Control	tunnel vent	tunnel vent	tunnel vent	tunnel vent
Cooling cells	no	no	no	no
Water drip or sprinkle	no	no	no	no
Do you use piglet heaters	heat lamps	heat lamps	heat lamps	heat lamps
Heating source for barn	propane	propane	propane	propane
Pig space cu ft per pig	14	14	14	14

Appendix Table 3. PPEFC farm inputs. Farm inputs are shared by both grow and sow barns.

Variable	**All states/years**
Distance to feed mill	60
Wet feed delivered per load	46000
percent from well	50
percent piped in	30
percent from other	20
Depth of well	80
HP of pump	7.5
Max flowrate of pump	180
percent solids in manure to fields	6.2
Distance to fields	3.5
Manure per truckload	40000
Dead animal disposal	Incinerating
Manure transport method	Tank Trucks
Pump type for umbilical hose	Electric
percent manure removed when emptied (all systems but subfloor)	90
Days between subfloor cleanouts	10
First day of the year on which manure is emptied	91
Second day of the year on which manure is emptied	244

6.2 National Aggregation Procedure

State burden per pig is calculated only for counties simulated - production weighted average of counties

$$\frac{stateBurden}{finishedPig} = \frac{\sum_{counties}\{\#County_{finishedPigs} * burden_{marketPig}\}}{\sum_{counties}\{County_{production}\}}$$

Average state burden for all marketed animals:

$$\frac{stateBurden}{LW_{marketed}} = \frac{\#State_{finishedPig} * StateBurden_{finishedPig}}{NASS_{LWProduction}}$$

Where, $\text{NASS}_{\text{LWProduction}}$ is the total mass of marketed animals in the state, which includes both finished pigs and culled sows. The state average burden is used for state level assessment, and the calculations below are, separately, used for national (or sector) level assessment.

Weighted estimate for national burden per finished pig based only on states simulated

$$\frac{nationalBurden}{finishedPig} = \frac{\sum_{states}\{\#State_{finishedPig} * stateBurden_{finishedPig}\}}{\sum_{states}\{\#State_{finishedPig}\}}$$

National burden per kg live weight:

$$\frac{nationalBurden}{LW_{marketed}} = \frac{\#National_{finishedPig} * nationalBurden_{finishedPig}}{NASS_{LWProduction}}$$