National Life Cycle Carbon Footprint Study for Production of US Swine

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Executive Summary

The National Pork Board commissioned the University of Arkansas' Applied Sustainability Center to conduct a life cycle assessment (LCA) of the US pork supply chain, with primary focus on defining greenhouse gas (GHG) emissions. GHG emissions are commonly defined in terms of the cumulative global warming potential (GWP) of all greenhouse gases emitted for a system or product, and in this case across the supply chain necessary to provide pork products to the consumer. The GHG of primary concern are carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O); and refrigerants. The GWP for a system is reported as carbon dioxide equivalents (CO_2e) derived by converting non-CO_2 gas emissions to an equivalent 'global warming potential' quantity of CO_2. The analysis was carried out for the functional unit of the consumption of one serving (4 ounces) of boneless pork. The system study boundaries encompassed feed production; pork production; delivery to processor; processing; packaging; distribution; retail; and consumption/disposal. The primary time frame for the study was 2008-2009.

The production system considered activities performed in support of pork production and delivery, extending to GHG burdens of raw material extraction such as fertilizer production, primary fuel extraction, delivery, combustion and, for electricity, transmission and distribution losses. The system specifically included production of polystyrene and other packaging material. Also, the impacts of distribution and refrigeration, as well as product loss through the supply chain, were included.

Raw data were provided from industry experts and standard pork industry handbooks. Regionally specific data for feed crops were taken from farm extension and the National Agricultural Statistical Service regarding the energy and GHG emissions associated with production. Additional input data for fuels and electricity consumption for crop production were obtained from the technical literature, state agricultural extension services, the US Department of Energy, the USDA, and other academic institutions. GHG emissions from manure were calculated, based on IPCC recommendations[1], from ASABE manure management guidelines[2] and from the Purdue Pork Industry Handbook[3]. Transport emissions from producer to processor and from processor to distributor were calculated from information provided from industrial sources. Cradle-to-grave contributions from packaging included production of raw materials (polystyrene, shrink wrap, paper) and ultimate disposal of the materials.

This report summarizes a scan level carbon footprint analysis for a single serving of pork prepared for consumption through evaluation of GHG emissions across the entire production and delivery system with relatively low resolution and high data aggregation – that is, it is not for a specific production system, but represents an overall average of US production, processing, and distribution systems. The available life cycle data, by production stage, and the methodology for calculation of the carbon footprint are described. It was found that the major impacts of pork production occur in crop production, manure management, retail distribution and consumption. The overall estimate of the carbon footprint for preparation and consumption of one 4 ounce serving was found to be 2.48 lb CO_2e with a 95% confidence band from 2.2 lb CO_2e to 2.9 lb CO_2e. Please note that the metric system was used for all our calculations and the final results were converted to English units for presentation. Overall, the contribution of emission burden for each stage was found to be approximately:

a) 9.6%: sow barn (including feed and manure handling);
b) 52.5%: nursery to finish (including feed and manure handling);
c) 6.9%: processing (5.6%) and packaging (1.3%);
d) 7.54%: retail (electricity and refrigerants);
e) 23.5%: the consumer (refrigeration, cooking, and methane from food waste in landfill).

Additional detail of the breakdown of contributions to GHG emissions is presented in Figure 1. It should be noted that these percentages are dependent on specific baseline assumptions in the model, two important baseline assumptions are that distiller's grains are included in the animal rations and that in-home preparation of the servings were for three people and a gas oven was used.

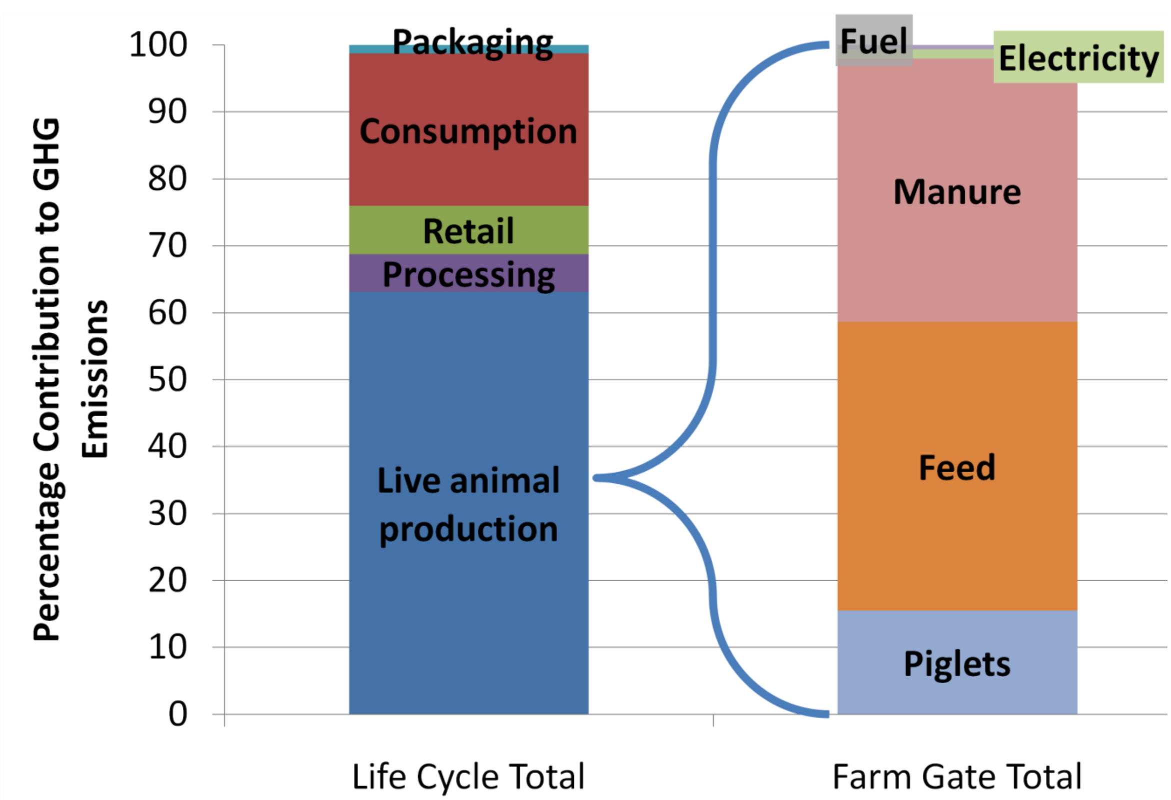

Figure 1. Relative contribution from different phases of the supply chain to the cumulative GHG

1 Introduction

The National Pork Board commissioned the University of Arkansas' Applied Sustainability Center to perform a life cycle assessment (LCA) of the pork supply chain which focused on defining greenhouse gas (GHG) emissions. The pork supply chain is broadly divided into 8 stages; each receiving separate analyses that were combined to provide the entire life cycle footprint. These stages are: feed production; live animal production; delivery to processor; processing; packaging; distribution; retail; and consumption/disposal.

Analysis of the pork supply chain can be used to provide the insight necessary to identify critical leverage points where, in turn, innovation can lead to increased efficiency in the supply chain while simultaneously leading to reductions in the carbon footprint of pork products. This project has been conducted in compliance with ISO 14040:2006 and 14044:2006 standards for life cycle assessment. It should be noted that a full LCA should also evaluate impact metrics that include other effects such as human health impact, ecosystem quality, and resource depletion. Because the intent of the study was to have the results reported to third parties, this project has received a post-hoc review by an external panel of experts led by Dr. Robert Anex, University of Wisconsin, Dr. Pascal Lesage, Interuniversity Research Center for the Life cycle of Products, Processes and Services (CIRAIG), École Polytechnique de Montréal, and Dr. Doug Reinemann, University of Wisconsin. The review panel had full access to the SimaPro model for their review. The review comments and authors' responses are presented as Appendix B following the body of the report.

2 LCA Methodology

LCA is a tool to evaluate environmental impacts of a product or process throughout the entire life cycle, which for agricultural products begins with production of fertilizers, and then crop cultivation, and animal husbandry, through processing, use and disposal of wastes associated with its final end-use. This includes identifying and quantifying energy and materials used and wastes released to the environment, calculating their environmental impact, interpreting results, and evaluating improvement opportunities.

This LCA has been structured following ISO 14040:2006, and ISO 14044:2006 standards which provide an internationally agreed method of conducting LCA, but leave significant degrees of flexibility in methodology to customize individual projects to their desired application and outcomes.

Figure 1 depicts the core LCA steps and highlights the iterative nature of the process. The goal and scope definition phase is a planning process, which involves defining and describing the product, process or activity; establishing the aims and context in which the LCA is to be performed; and identifying the life cycle stages and environmental impact categories to be reviewed for the assessment. The depth and breadth of LCA can differ considerably depending on the goal of the LCA.

The life cycle inventory analysis phase (LCI phase is the second phase of LCA) is an inventory of input/output material and energy flows with regard to the system being studied; it involves identifying and quantifying energy, water, materials and environmental releases (e.g.: air emissions, solid wastes, wastewater discharge) during each stage of the life cycle.

The life cycle impact assessment phase (LCIA) is the third phase of the LCA. This step calculates human and ecological effects of material consumption and environmental releases identified during the inventory analysis. For this study, the Global Warming Potential (GWP) was analyzed and reported. GWP is an important effect related to climate change and is one of several common LCIA impact categories. Others include eutrophication, acidification, ozone depletion, land use, etc. Readers should be cautioned that interdependencies may exist between impact categories and poor decisions can be made when only a single impact metric is used as the basis.

Life cycle interpretation is the final phase of the LCA procedure, in which the results are summarized and discussed. Its goal is to identify the most significant environmental impacts and the associated life cycle stage, and highlight opportunities for potential change or innovation.

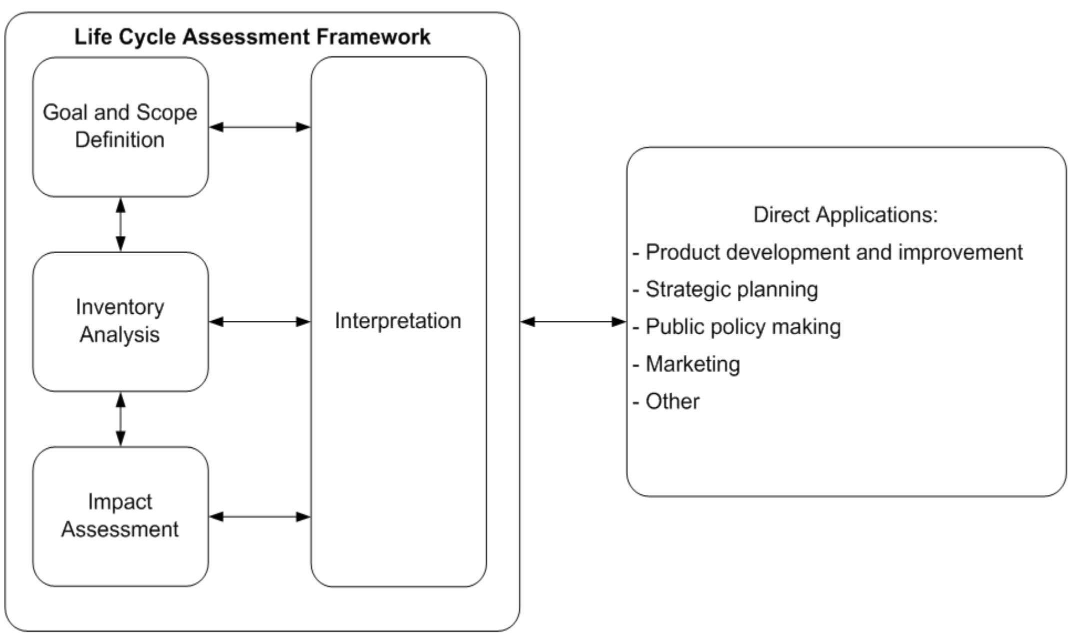

Figure 2. Stages of a life cycle assessment

2.1 Goal and Scope Definition

2.1.1 Goal

Determine GHG emissions associated with delivery, preparation, and consumption of one serving of pork to US consumer. Because of the strong link between energy consumption and greenhouse gas emissions, it is frequently the case that high greenhouse gas emissions are indicative of opportunities for improved energy efficiencies or conservation. In addition, this analysis will provide an understanding of the industry's baseline level of greenhouse gas emissions which will be beneficial if voluntary carbon trading markets become viable in the future.

2.1.2 Functional Unit

The functional unit of this study was one 4 ounce (uncooked weight) serving of boneless pork prepared for consumption by a US consumer. We do not differentiate among cuts of meat in this analysis.

2.1.3 Project Scope and System Boundaries

This life cycle assessment was a cradle-to-grave analysis of the carbon footprint or global warming potential of the production and consumption of boneless pork. The system boundaries, shown schematically in Figure 3 (including the gray boxes), encompassed effects beginning with GHG emissions associated with raw material extraction from nature through greenhouse gas emissions from either landfill or municipal waste incineration of the packaging. Incidental effects such as employee's commutes, nor the cost of heating the farmer's residence have not been included. In addition, we have not specifically accounted for long-term storage of carbon in non-consumed parts of the animal specifically leather and meet which may not decompose in a landfill. Nor does the scope of this project extend to other potential environmental effects such as nutrient runoff, topsoil loss, or depletion of freshwater supplies; it focused on evaluation, at the national scale, of the global warming potential attributable to production and consumption of pork in the United States. The primary time frame for the study is 2008 - 2009.

2.1.4 Allocation

Where co-products are produced, an allocation of burdens associated with the unit process is necessary. We evaluated allocation choices by the ISO hierarchy for allocation. There are three stages in the supply chain where allocation occurs: first for byproducts of feed processing (e.g., distiller's grains and soy meal); second at the processing gate where allocation between dressed carcass and rendering

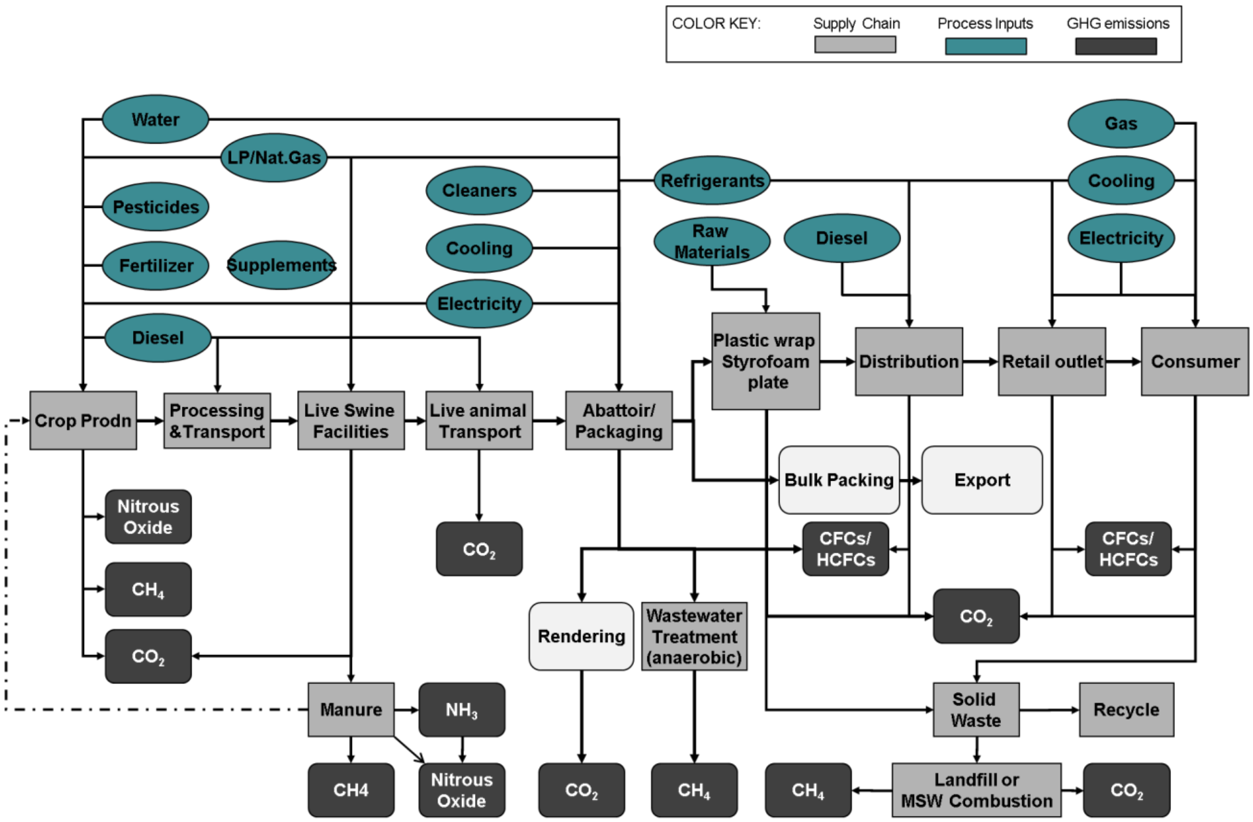

Figure 3. Schematic of pork production supply chain showing major inputs and outputs relevant to greenhouse gas emissions. Boxes with white fill are not included within the system boundary.

products occurs, and finally at retail and consumption where an allocation of refrigeration burdens and a fraction of consumer transport of groceries is necessary.

The ISO approach recommends system separation as highest priority. For the allocation necessary in this project there exists a situation of joint production, where the relative quantities of, for example meal and oil, cannot be independently varied (beyond variation in the oil content of the seeds) which causes the allocation priority to be system expansion. As this is a scan type or streamlined LCA, the analysis required to identify the substitute products and ensure that quality LCI data exist was deemed out of the project scope, and we have adopted economic value allocation (lowest of ISO hierarchy) as a base case approach and consider a mass allocation for feed byproducts for comparison. Due to the proprietary nature of economic data at retail, we have used a shelf space and sales approach to estimate an appropriate allocation of retail and in-home burdens.

2.1.5 Cut-off criteria

The cut-off criterion for the study, and generally applied at the scale of an individual stage of life cycle, is as follows: if a flow contributes less than 1% of the cumulative global warming potential, it may be omitted from the model; however, small flows are not omitted when data are readily available. Specific processes that were excluded on this principle were insemination and other veterinary inputs; employee commuting and incidental energy consumption associated with on-farm residences or offices were also estimated to be deminimus contributions. We did not include accounting, legal or other services for individual farms, processors or retail outlets. In addition to these exclusions, we did not account for infrastructure.

2.1.6 Life cycle impact assessment

For this project, a single impact assessment metric was chosen, global warming potential (GWP). We have adopted the most recent IPCC recommended 100 year time horizon GWP equivalents for this project[4]: CO_2 = 1; CH_4 = 25; and N_2O = 298. Global warming potential equivalents are also presented for most common refrigerants in this document. Biogenic carbon and methane impacts are discussed in §2.3.3.

2.1.7 Audience

Stakeholders in the pork industry value chain are the intended audience for this study. This study is not intended for comparative purposes, but is intended for third parties, and as such has undergone an external review, described above. The study has been undertaken primarily as a tool to identify opportunities for increasing efficiency and to provide a baseline evaluation of the industry's contribution to the U.S. greenhouse gas emissions inventory. Consumers increasingly express an interest in understanding of the environmental impacts of the products they purchase, and thus consumers represent a second potential audience for the study results. The LCA supports the pork industry's ability to work proactively with retailers to educate consumers about agricultural and food sustainability issues.

2.2 Conceptual farm production model

To simplify mass and energy accounting we have chosen not to use a barn or batch of weaned piglets as the computational basis, instead the computational farm model is based on the productive life of one sow. The average number of litters (parities) and the number of piglets per litter are used to determine the total feed and on-farm energy requirements. The cumulative and GWP impacts from all the inputs are divided by the total mass of the finished animals produced from that sow. A schematic is shown in Figure 4.

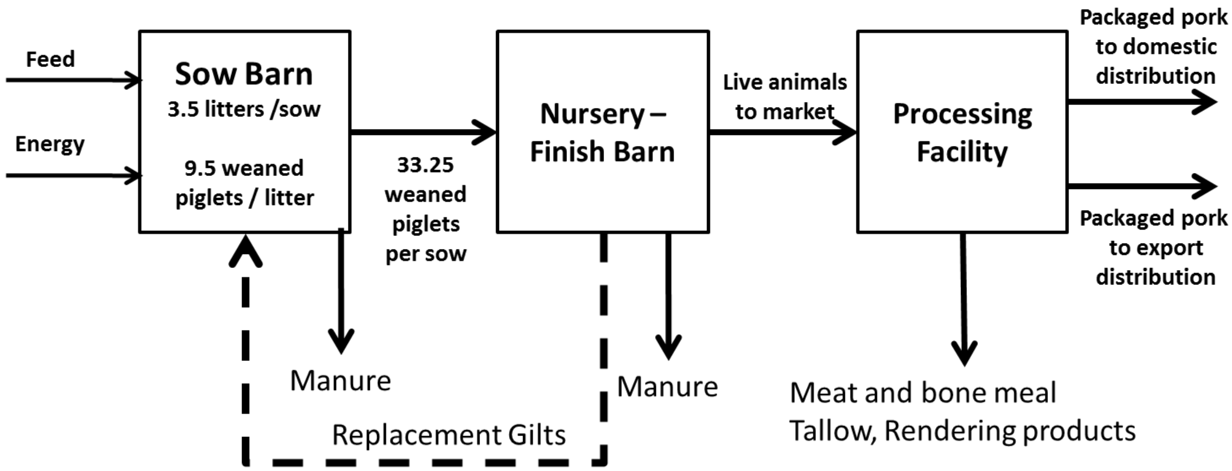

Figure 4. Schematic of simplified pork production. Material and energy flows are integrated over the productive life of a single sow. The farm gate cumulative consumption of feed and energy required to finish all the litters produced by one sow is allocated to the total finished weight of her litters.

Thus the farm-gate footprint is: $\frac{\sum GWP_{inputs} + \sum GWP_{manure}}{268lb(finished\ wt) * 3.5litters * 9.5piglets/litter}$ on a live weight basis; the inputs in the equation include the replacement gilts. This result can be converted to a carcass or boneless basis using the live-to-purpose conversion of: 0.75 lb carcass per lb live weight, and the carcass-to-boneless conversion: 0.65 lb boneless meat per lb carcass.

2.3 Life cycle inventories

A previously conducted literature review is used as the basis for much of the life cycle inventory data[5], and additional discussions with industry representatives and other experts helped fill in the data gaps. The production system encompassed activities performed in support of pork production and delivery extending to GHG burdens of raw material extraction for fertilizer production, primary fuel extraction, delivery, combustion and, for electricity, transmission and distribution losses. The system included production of polystyrene foam shells, shrink wrap, and adsorbent pads used to package meats in supermarkets. We also included the impacts of distribution and refrigeration. The life cycle calculation approach adopted for this work was largely process based; we used Economic Input-Output data for whey in the animal ration because suitable process based datasets were not readily available. This was to avoid errors associated with exclusion of GHG emission burdens. The inclusion of EIO data does add some uncertainty to the analysis because of differences in the underlying basis for EIO estimates of impact contributions. In particular, EIO System boundaries are more extensive than boundaries for process based analysis. We have included an analysis of the percentage of the total GHG emissions arising from EIO datasets in §4.2.5. It should also be noted that some data are not from the US, in particular much of the background data used in the study comes from the European based data in EcoInvent and may not be completely representative of US conditions. These data include activities like petroleum refining and some electricity generation technologies (e.g., wind and hydro) for which US data do not exist. Foreground processes (those typically under direct control of the main supply chain actors) are all linked to the US electricity grid mix; however, many background processes, taken without modification from EcoInvent, remain linked to EU electricity mixes. In our judgment, any differences in these background processes will not affect the study conclusions.

2.3.1 Crop production

In consultation with industry experts, we have identified the most common feeds[6,7] and have collected available information from farm extension and the National Agricultural Statistical Service regarding the energy and greenhouse gas emissions associated with production of these crops.

2.3.1.1 Corn, DDGs, Soybean Meal

Two main sources of agricultural data were used: crop production data and agricultural chemical usage statistics on a state-by-state basis from the USDA National Agricultural Statistics Service[8]. Figure 5 shows the key data sources and steps in calculating GHG emissions per lb of crop produced. Data on chemical usage (fertilizers, pesticides) were combined with crop production data to determine these inputs per lb of crop harvested.

Input data for fuels and electricity consumption for crop production were obtained from the technical literature, state agricultural extension services, the US Department of Energy, the USDA, and other academic institutions. Fertilizer and fuel consumption for crop production were used as an input data for calculations performed using the SimaPro 7.1 software. The EcoInvent database was used to provide

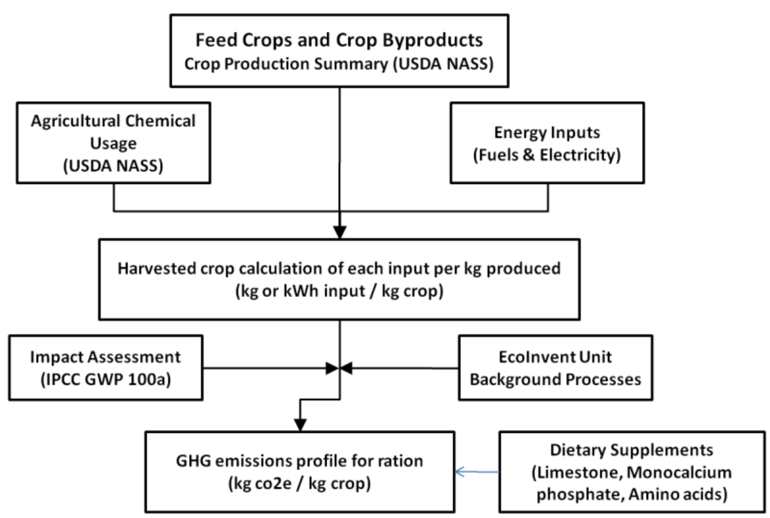

Figure 5. Information diagram for calculating GHG emissions per amount of feed crop produced.

upstream/background information (e.g., production of fertilizer, diesel, natural gas, etc) and the IPCC GWP 100a impact assessment methodology was used to summarize the GWP of cradle-to-gate crop production. Industry estimates were used to calculate the transportation burden associated with moving the grains to feed mills which are typically near animal production facilities.

Distiller's grain production was modeled using an EcoInvent unit process created for US conditions. This unit process accounts for the fermentation, drying and other processes in a typical US corn ethanol plant. The allocation between ethanol and DDGs is based on economic value of the products, except that the energy for drying the distiller's grains to facilitate longer distance transport is allocated entirely to the DDGs. The allocation of other inputs is, including the corn grain, is 1.2% allocated to distiller's grains; this allocation fraction was reported on the EcoInvent website, and adopted as the baseline economic allocation for this study. Information available from the Agricultural Marketing Resource Center[9], combined with an average production of 2.8 gallons of ethanol and 17.4 lbs of distillers grain per bushel of corn results in an average allocation of 18.5% to distiller's grains. Using this alternate economic allocation increases the footprint of the DDGs from 0.94 lb CO_2e/lb DDGs to 1.1 lb CO_2e/lb DDGs.

We adapted the recent United Soybean Board LCA for the production of biodiesel from soy oil as the basis for the soybean meal carbon footprint[10]. An economic allocation among soy oil, meal and hulls was used. Economic allocation fractions were meal: 56.5%; oil: 41.6%; hulls: 1.9%, and mass allocation fractions (for sensitivity analysis) were meal: 74.25%; oil: 19.34%; hulls: 6.41%.

2.3.1.2 CO_2e emissions from lime, urea, pesticides, and fertilizer application

Nitrous oxide emissions attributed to crop production were taken to be 1% of applied nitrogen[1]. No distinction between inorganic fertilizer and manure application was made in regard to direct nitrous oxide release. However, the ammonia volatilization fraction for applied manure was taken as 20% rather than 10%, leading to slightly larger indirect N_2O emissions from manure N than inorganic N. For the scale of the analysis conducted, there is not sufficient resolution in the underlying data regarding crop rotation, tillage, and soil type to justify more complex estimation of the N_2O emission. GWP burdens associated with other fertilizers, including lime, and pesticides were accounted for in the inventory data obtained from EcoInvent. Decomposition of crop residue contributes some N to the soil nitrogen cycle, and results in additional N_2O emission. The IPCC recommendations for estimation of crop residue related emissions have been followed[11].

2.3.1.3 Calculation of the cradle to mouth feed footprint.

Note that our initial analysis defined dry distiller grains (DDGs), a byproduct of corn ethanol production, as an important contributor to GWP of the feed. We have performed an analysis using two diets: one with and one without DDGs[6],[7]. Estimated feed consumption and composition are given in Table 1 through Table 4. Assuming 9.5 piglets per litter, the total quantity of each feed component consumed by all the animals passing through the system over the course of 3.5 litters (on average) for a sow was calculated. In essence, this is an integration of all of the feed crossing the farm gate resulting in an average production of 32.25 finished pigs plus one sow. The total quantity of each feed component was multiplied by the carbon footprint for the production of that feed to give the overall feed footprint. Tables 1 and 2 present the information for a single lactation, and thus, on average, 3.5 times that amount of feed would be accounted for in production of 32.25 finished pigs plus one sow. In Tables 3 and 4, the ration being fed is keyed to the animal's bodyweight (BW); all animals are assumed to reach a finish weight of 268 lb.

Table 1. Typical Sow Diet – Without DDGs

Sow Feed			
	Breeding	Gestation	Lactation
Est. feed, lb/sow	**50**	**600**	**252**
% Corn	66.1	81.5	66.1
% DDGS	0.0	0.0	0.0
% SBM	27.0	14.5	27.0
%FAT	2.0	2.0	2.50
%Supplement	0.7	0.7	0.7
%Dical/limestone	2.9	2.9	3.0

Table 2. Typical Sow Diet – With DDGs

Sow Feed			
	Breeding	Gestation	Lactation
Est. feed, lb/sow	**50**	**600**	**252**
% Corn	58.0	53.0	58.0
% DDGS	10.0	30.0	10.0
% SBM	25.0	11.0	25.0
%FAT	2.0	2.0	2.35
%Supplement	0.7	0.7	0.8
%Dical/limestone	2.5	2.5	2.9

2.3.2 On-farm manure management

Different manure management systems result in different quantities of greenhouse gases, primarily methane and nitrous oxide, emitted to the atmosphere. The IPCC provides guidance on estimating the quantities of greenhouse gases which are emitted as a function of the specific management system[1]. We have used the American Society of Agriculture Engineers (ASAE)[12] recommendations to predict the quantity of manure generated, as well as to estimate the amount of nitrogen excreted in the manure. Manure management systems included in the model are deep pit, anaerobic lagoons, solid store, liquid slurry and pasture. Each can be modeled separately for scenario comparison as presented in §3.3.2 below. In addition, for national scale analysis, the fraction of manure handled by each of the practices is accounted at a regional scale (See Table 5).

Table 3. Nursery and Grow-Finish Typical Diet – Without Distillers Grains

Pigs	Nursery			Grow-Finish				
	Phase I	Phase II	Phase III	Grower I	Grower II	Finisher I	Finisher II	Finisher III
BW, lb	11-15	15-25	25-50	50-95	95-140	140-185	185-230	230-270
Gain, lb	4	10	25	45	45	45	45	40
Days in period	7	14	21	24	23	22	23	24
Est. feed, lb/pig	**5**	**15**	**48**	**100**	**113**	**131**	**148**	**145**
% Corn	37.9	51.9	59.2	62.8	68.5	74.3	80.9	83.9
% DDGs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% SBM	20.0	28.0	34.8	31.3	26.0	20.8	15.3	12.3
% Dried Whey	25.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0
%Fat	5.0	3.0	1.5	2.5	2.5	2.5	1.5	1.5
%Supplement	3.3	3.1	2.0	1.1	1.1	1.0	0.9	0.9
%Dical/limestone	1.3	1.8	2.6	2.3	1.9	1.5	1.5	1.5
%bone/blood meal	7.5	2.3	0.0	0.0	0.0	0.0	0.0	0.0

Table 4. Nursery and Grow-Finish Typical Diet – With Distillers Grains

Pigs	Nursery			Grow-Finish				
	Phase I	Phase II	Phase III	Grower I	Grower II	Finisher I	Finisher II	Finisher III
BW, lb	11-15	15-25	25-50	50-95	95-140	140-185	185-230	230-270
Gain, lb	4	10	25	45	45	45	45	40
Days in period	7	14	21	24	23	22	23	24
Est. feed, lb/pig	**5**	**15**	**48**	**100**	**113**	**131**	**148**	**145**
% Corn	33.8	43.9	47.2	50.7	56.3	62.1	68.6	83.9
% DDGS	5.0	10.0	15.0	15.0	15.0	15.0	15.0	0.0
% SBM	19.2	26.2	32.2	28.7	23.6	18.3	12.9	12.3
% Dried Whey	25.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0
%Fat	5.0	2.9	1.4	2.3	2.3	2.4	1.4	1.5
%Supplement	2.0	2.2	1.9	1.1	1.1	1.0	0.9	0.9
%Dical/limestone	1.2	1.7	2.4	2.1	1.7	1.3	1.3	1.5
%bone/blood meal	7.5	2.3	0.0	0.0	0.0	0.0	0.0	0.0

2.3.2.1 Methane and nitrous oxide emission due to manure management

We employed standardized methodologies as laid out in the IPCC 2006 guidelines in estimating the annual CH_4 and N_2O emission factor (EF_T) from manure[1]. We have used the ASABE guidelines to define the average manure characteristics (Table 6), in particular the volatile solids content which is significant in determining the quantity of methane that can be produced under anaerobic conditions.

Table 5. Production regions used in national scale analysis and weighted fraction of animals with specific manure management practices.

		Fraction of animals in region with manure managed by:					
	States	Pasture	Solid Store	Liquid Slurry	Anaerobic Lagoon	Deep Pit	1000 head*
Region 1	CT, ME, NH, VT, MA, RI	0.509	0.022	0.135	0.102	0.231	23.7
Region 2	NY, NJ	0.184	0.040	0.215	0.154	0.407	194
Region 3	DE-MD, PA, WV, VA	0.024	0.049	0.218	0.265	0.445	2335
Region 4	AL, FL, GA, KY, MS, NC, SC	0.006	0.040	0.065	0.574	0.315	14912
Region 5	IL, IN, MI, MN, OH, WI	0.006	0.050	0.275	0.168	0.502	32800
Region 6	AR, LA, NM, OK, TX	0.015	0.038	0.066	0.569	0.313	5621
Region 7	IA, KS, MO, NE	0.002	0.044	0.170	0.382	0.402	44277
Region 8	CO, MT, ND, SD, UT, WY	0.007	0.053	0.263	0.178	0.499	4349
Region 9	AZ, CA, HI, NV	0.075	0.032	0.091	0.488	0.314	238
Region 10	AK, ID, OR, WA	0.310	0.035	0.190	0.133	0.332	94.2
National		0.007	0.045	0.181	0.352	0.415	104844

* Based on USDA sales of finished hogs, summed from state level data

Table 6. Average manure characteristics as predicted by ASABE equations[12].

	TS	VS	COD	BOD	N	P	K
				kg/Finished animal			
Nursery	4.8	4	4.4	1.5	0.41	0.068	0.16
Grow-finish	56	45	47	17	4.7	0.76	2
				kg/animal/day			
Gestating sow	0.5	0.45	0.47	0.17	0.032	0.009	0.022
Lactating sow	1.2	1	1.1	0.38	0.085	0.025	0.053

Note that manure excreted by piglets is included in the sow estimate.

The temperature is also an important parameter in the estimation of methane release associated with each of the manure management techniques. U.S. monthly average temperature data were extracted from the National Climatic Data Center. This temperature information was used in estimation of the methane emissions from manure handling to account for the difference in mean temperature among the 10 USDA production regions.

Other variables used in the model are the volatile solids (VS_T) of the manure and the maximum methane production capability (B_0 = 0.48 m^3CH_4/kg VS) (Table 10 A71)[1]:

$$EF = (VS * 365) * B_0 * 0.67 \frac{kgCH_4}{m^3CH_4} * \left[\sum \frac{MCF_{S,K}}{100} * MS_{(T,S,K)}\right]$$

EF is the emissions in kilograms methane per animal per year and

MCF is the methane conversion factor (percent)- a function of both temperature and manure management system.

MS is the fraction of volatile solids that is handled by each manure management system.

Based on herd demographics data obtained from the census of agriculture in 2007 (Figure 6), and information provided from the EPA Greenhouse Gas Emission Inventroy[13] regarding the fraction of operations that utilize specific manure management practices by state. The data presented in the EPA document is based on the number of operations utilizing each practice, however, for an accurate analysis, it is necessary to estimate the number of animals associated with each management practice. In this report, we have followed the USDA production regions defined in Table 5.

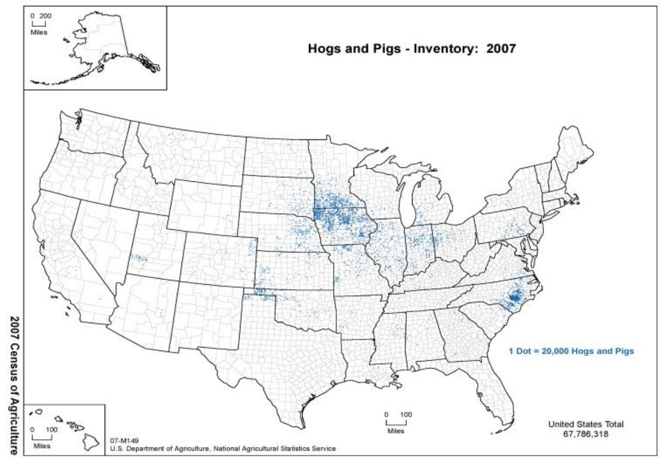

Figure 6. Distribution of hogs in the U.S.

To estimate the number of animals associated with each manure management practice, the following assumptions were made: regional averages for percent adoption of each manure management system were calculated by summing the state by state reported values[13]; operations with 50 or fewer head were assumed to be pasture based; operations between 50 and 200 head were assumed to be distributed as reported (that is by number of operations reporting each practice); operations with more than 200 head were assumed to have no animals on pasture, and the management systems were distributed according to a re-normalized adoption rate. This renormalization ensures that the total animal population is fully accounted. Animal numbers were estimated from both the agriculture census (2007) and from federally inspected slaughter data. Both sources correlate well with the food availablity data estimate of 47.3 lb pork consumed per capita in the US.

Nitrogen containing compounds found in manure can be converted to nitrous oxide and released to the atmosphere by both direct and indirect routes. Nitrous oxide (N_2O) and nitrogen gas (N_2) are both produced in the denitrification step of the nitrogen cycle. Nitrous oxide emissions are strongly dependent on the specific conditions encountered in the manure management system. The presence of oxidized forms of nitrogen is necessary, and therefore significant nitrous oxide release only occurs in circumstances where anaerobic conditions which produce oxidized forms of nitrogen are followed by anaerobic conditions necessary for the denitrification step. For this study, we followed the IPCC tier two recommendations in that US specific nitrogen excretion rates were adopted[2]. Direct emissions were calculated by:

$$N2O = \left[\sum Head * N_{ex} * MS_i\right] * EF_i * \frac{44}{28}$$

Where head is the number of animals with an annual nitrogen excretion rate given by N_{ex} which is handled in manure management system MS_i with an emission factor for the management system of EF_i. The factor 44/28 converts nitrogen in the manure to nitrous oxide emissions through the ratio of molecular weights. As indicated above, we are considering two primary manure management systems. The emission factor for deep pits is 0.002 (lb N_2O-N)/(lb N excreted), and the emission factor for liquid/slurry ponds or tanks is zero if no natural crust cover is present and is 0.005 (lb N_2O-N)/(lb N excreted) for cases when a natural crust cover forms on the surface.

Indirect emissions of N_2O result from ammonia and NO_x volatilization followed by deposition onto soil where denitrification occurs. Indirect emissions were calculated by:

$$N2O = \left[\sum N_{vol} * MS_i\right] * EF_i * \frac{44}{28}$$

Where N_{vol} is the quantity of nitrogen volatilized from manure management system, MS_i, and EF_i is the fraction of all volatilized nitrogen converted to N_2O. A similar expression is used to estimate indirect N_2O emissions associated with leaching and runoff of nitrates. The fraction of nitrogen lost by volatilization from deep pits is estimated to be 25% with a range of 15 to 30%. For anaerobic lagoons, the volatilization losses are expected to be 40% with a range of 25 to 75%. The conversion factor, EF, to N_2O for volatilization losses is 0.01 (lb N_2O-N)/ (lb N volatilized) and for leaching and runoff it is 0.0075 (lb N_2O-N)/(lb N leached).

2.3.3 Biogenic carbon

For the purpose of this study, we have assumed most crop land under cultivation in support of the pork production has seen stable production practices in recent history. Because of this it is believed that there is relatively little change in soil carbon content, and therefore sequestration of carbon dioxide by the plants as they are growing has not been accounted. This simplifies the modeling of the system because it is not necessary to account for respiration by the animals, nor for subsequent respiration by humans as the meat is consumed. There is also some long term storage of carbon in parts of the pig that are not consumed but the end up as for example leather or wasted me meat in a landfill. This represents a small quantity of carbon which is not released back to the atmosphere; however the effects of this long-term storage were not accounted in this study.

It is well documented that when tillage practices change from conventional to conservation or no till then there can be measurable increases in the carbon content of the soil[14,15,16,17]. Thus for site specific conditions where tillage practices have changed, it would be appropriate to include sequestration of below ground biomass to the extent that it can be documented; however, at the scale of this analysis, inclusion of site-specific tillage practice was not feasible. One particular point regarding biogenic emissions in the pork industry is that a portion of the carbon which has been sequestered during plant growth is released to the atmosphere as methane as a result of manure management practices. Because of the difference in global warming potential of methane and carbon dioxide it is clear that the methane cannot be treated as a carbon-neutral emission; therefore biogenic methane is accounted, both as enteric methane (very small amount as pigs are non-ruminant animals) and methane released during manure management.

2.3.4 Farm to Processor Transportation

Discussions with industry experts provided insight into the structure and characterization of transportation from farm to processor. We used an estimate of 500 miles transportation distance between the farm and the pork processor. These calculations are based on an average of 160 head with a mean weight of 268 pounds per truck for delivery of finished hogs.

2.4 Pork Processing and Packaging

Data were obtained from industrial sources, and aggregated to mask confidential, business sensitive data. We received data from over 10 meat processing facilities. The information included the quantity of processed meat leaving the facility, the amount of electricity, natural gas, and other fuels consumed for the entire facility. Estimates of greenhouse gas emissions from onsite waste water treatment facilities, and loss of refrigerants were also reported. Industrial GHG reporting is typically based on finished product leaving the facility and does not specifically account for rendering products; however, in life cycle assessment, when a system has multiple products, each of which have economic value, it is standard practice to assign some of the environmental impact burden from that process to each of the co-products. The question of how to allocate among the co-products can be difficult to answer. International standards recommend system expansion, where credit is taken for production of an item that is equivalent to the environmental burdens associated with production of that same item from a different and independent system. However, in this situation, because all processing facilities had associated rendering facilities, and the specific co-products and quantities were not reported, determining the products substituted for the application of system expansion was not possible. Some standards recommend a physical causality modeling approach, a reasonably detailed engineering model of the entire processing facility is necessary to implement this recommendation; a complete mass and energy balance is used to determine precisely how much energy is associated with each co-product from the facility. This approach is beyond the scope of the current project. An economic allocation among the co-products is often the most practical approach to this allocation of environmental burden, and was adopted for this analysis. One approach to arrive at an economic allocation is to consider data from the US economic census[18]. Although these in NAICS codes include meats other than pork, as the basis for an initial allocation ratio, in the absence of other data, these values can be used. The allocation ratio calculated using this method assigns 89% of the greenhouse gas burden to the meat processing and 11% assigned to the products from rendering operations. We have also included an export stream in the analysis; however, on a per serving (or kilogram) basis, this does not affect the result. There are differences in the cut of exported meat as well as its packaging. However, differences in impacts associated with different cuts of meat are not available, and very likely to be extremely small. Packaging for exported meat is outside the system boundary for domestic consumption. The export volume does not affect the overall contribution per pound of domestic pork consumed in the US, as the burden of the exported pork can be considered to follow the meat to its point of consumption.

Table 7. Economic census data used for allocation in processing and packaging

NAICS Code		Value of primary products shipments ($1,000)
311612	Meat processed from carcasses	35,945,422
311613	Rendering and meat byproduct processing	4,476,039

2.4.1 Methodology

The data provided from industrial sources consists primarily of direct on site GHG emissions and indirect emissions, typically from production of electricity. We have constructed unit processes in SimaPro, linked to EcoInvent upstream processes, where the average reported values for fuels and electricity were used as inputs, to calculate the full system burden.

2.4.2 Uncertainty

Monte Carlo simulation was used to address uncertainty and ranges of emission factor data and input information. When provided, we used the probability density functions for unit processes available in the EcoInvent, or other databases. For unit processes which were created for this project, the reported variation, or calculated variability, was used in conjunction with an assessment of the data quality following the EcoInvent pedigree hierarchy to provide a log normal probability density function for uncertainty analysis.

2.4.3 Electricity

There are three electricity production regions in the U.S.; these regions are Eastern Interconnection, Western Interconnection, and the Electric Reliability Council of Texas (ERCOT) Interconnection[19]. Use of the three main interconnections as the basis for calculating environmental burdens from electricity production are better than national, state, or even utility-level emission factors because there is virtually no electricity energy transfer between the interconnect grids, so at this level there is some certainty about the actual fuel mix used to provide electricity. In practice, for this model, we generally do not know which the appropriate grid region is, and therefore, with the exception of regional crop production have used the US national primary fuel mix for calculation of GHG emissions associated with electricity consumption. In addition, while we have used US primary electricity unit processes for foreground processes (those created for this project), we have not modified the entire EcoInvent database, and thus most background processes are still linked to EU electricity processes.

2.4.4 Fuel Energy

Ecoinvent fuel energy unit process emissions include pre-combustion (that is emissions from production and delivery of the fuel) and on-site combustion. The majority of fuel energy in pork processing comes from natural gas and electricity.

Emissions from transportation were calculated using EcoInvent unit processes combined with industry estimates for haul distances for feed to milling and from the mill to the farm. Industry reported fuel consumption was used to estimate transportation mileage, which is the basic unit for consumption of transportation fuels in the EcoInvent database.

2.4.5 Packaging Materials

For retail distribution in the United States, most meats, including pork, are packed on a polystyrene plate with an absorbent pad and wrapped with a stretch wrap plastic film. We have estimated 8.8 g of polystyrene[20] and ½ g of stretch wrap material per pound of packaged pork. The specific makeup of absorbent pads is generally proprietary. We used information in a patent[21] to represent a typical absorbent pad made from Vicose and expanded Vicose as the basis for the calculations.

2.5 Retail

After distribution from the processor to the retail gate, pork is displayed for consumer purchase. During this phase, there are four distinct emissions streams: refrigerant leakage, refrigeration electricity, store overhead electricity and fuel (natural gas). Estimates of the sales volume, space occupancy, and energy demands of pork were used to determine the burden of this supply chain stage. Overhead electricity demand activities allocated to pork include ventilation, lighting, cooling, space heating, water heating, and other miscellaneous electrical loads (e.g., free standing refrigerators). Based on the 2007 National Meat Case Study[22] pork products occupy 19 - 20% of shelf space in the meat/poultry/fish category; based on a combination of information from the Food Marketing Institute (price data) and meat sales volumes (USDA), we estimated that 21.5% of meat sales. Using this information in combination with data from the Food Marketing Institute[23] on the fraction of grocery sales by department and the average supermarket size, we calculated that pork represents approximately 2.7% of typical supermarket sales and 6.3% of refrigerated sales. These fractions were used as allocation fractions for refrigerated space. Buzby et al., in a study on the loss of perishables in supermarkets, reported average loss of pork is 4.4%[24]. We also evaluated the allocation of retail emissions on a space occupied basis. Information from a proprietary study reports that approximately 57 linear feet of refrigerated shelf space is devoted to pork products in a typical grocery configuration with a total of 4300 refrigerated linear shelf feet and 21980 linear feet of total shelving. This results in 1.32% of total refrigerated store shelving and 0.258% of total shelving space. We have included a sensitivity analysis of these allocation approaches (economic and physical) § 3.4, Figure 14.

2.5.1 Refrigerated Space Burden

The storage and sales of pork to the retail consumer carries a GHG burden from energy use (electricity and natural gas), and fugitive emissions associated with refrigerant loss. Based on average store square footage, consumer-facing shelf space, and end-use energy demands[25,26,27], average electricity, refrigerant, and natural gas activity flows per lb pork sold were developed. An average yearly loss of refrigerants was included in the GHG emissions estimate[25,27]. R22 and R404A were assumed to be used at 54% and 46%, respectively[25].

2.6 Consumer

Impacts accounted in this phase include transport from retail to home, refrigeration and cooking energy and food loss or waste. Consumer transportation related emissions were allocated using the same economic and space based allocation fractions (whole store allocation basis – 0.258% with an assumed 5 mile round trip for grocery store purchases). The fundamental assumption in this allocation approach is that the composition of the products on supermarket or grocery store shelves is an approximation of the average US household purchasing and storage. We also took either the economic or shelf space estimates from supermarket refrigerated space as the allocation fractions for in-home refrigeration electricity. Estimates of the consumer cooking energy for gas and electric ovens were made. Cooking energy requirements were estimated using information from the US EPA Energy Star program. Both pre-heat and cooking times were included, but assumed no additional idle time. Also assumed was that the cooking energy was based on cooking eight 4-ounce servings (e.g., as a 2 pound tenderloin to be cut into individual servings after being cooked). Cooking yield for pork depends on the method, but ranges from 71 to 75%[28,29]. The Economic Research Service of the USDA provides annual estimates of loss-adjusted food availability. The estimated loss at consumer phase is 39%; some current research suggests that this may be closer to 29%[30]. This includes spoilage, plate waste, and cooking weight loss. As indicated above there is a 21 to 25% weight loss due to cooking, and we have not included this weight loss in the model calculations; we assumed a combined 10% spoilage and plate loss.

2.6.1 Post-Consumer Solid Waste

There is a relatively small quantity of post-consumer waste generated, and it is modeled using an EcoInvent process for landfill disposal. We estimated the potential methane emission from meat disposed in landfills using information reported by Cho and Park[31]. The elementary flow estimate from these data is 0.344 lb CH_4 per lb volatile solids disposed. Cooked pork meat is 97% volatile solids. This estimate likely represents an upper limit to the methane generated when meat is disposed in landfills because the study was focused on energy recovery from anaerobic digestion, and did not replicate conditions in a landfill.

2.7 Software, Database and Model Validation

The LCA model was created using the SimaPro Software system for life cycle engineering, developed by Pre, a Netherlands based company. The EcoInvent database was used for the life cycle inventory data of the raw and process materials needed for background processes. All computational modules are documented with reference citations to external source data also available in the literature review[5].

3 Scan level carbon footprint results

The model for the footprint is based on a 2 barn system: Breeding/Gestation/Lactation barn (or Sow Barn) followed by a Nursery/Finish (N/F) barn. We recognize that this is not representative of all configurations; however, addition of a third nursery barn and changing the N/F barn to a Grow/Finish barn will have relatively small impact in terms of a high level scan. Transportation of animals between the nursery and grow-finish barns will be the major additional source of emissions in this case. The model is built to account for an entire life cycle of a single sow, and specifically includes gilt development and multiple litters (parities). The N/F barn accounts for all the piglets from all parities grown to full weight. Tables 1 through 4 present the model diets.

3.1 Life Cycle Phases

The model follows the structure shown in Figure 2. Each unit process, or stage, has inputs and outputs that contribute to calculation of the overall GHG emissions of the system. The model parameters are listed in Tables A-1 and A-2. In the following sections, we present the overall footprint and several gate-to-gate partial footprints to provide a reference to other published LCA results.

The results are presented in a series of network diagrams which show the relative impacts of different phases of the pork production and delivery system. The truncated example of one of these diagrams is shown in Figure 7. In the network diagrams, each box or node represents a particular material or flow which contributes to the global warming potential of the pork production system. The box could contain materials such as corn feed or soybean meal, or represent energy consumption in the form of electricity or other fuels. In addition, examples of the process (or material) include the meat packing facility, or for in-home consumption. The width of the connecting lines represents the relative

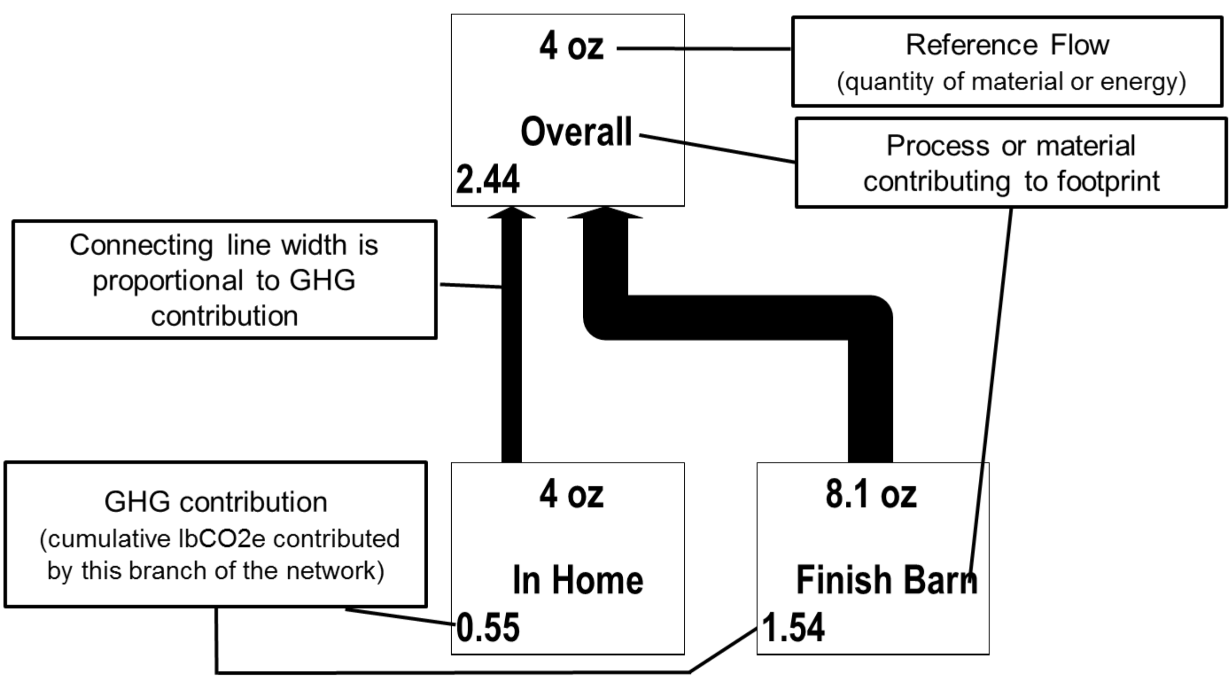

Figure 7. Network diagram key.

contribution from the particular unit to the whole global warming impact. The contribution shown in each box is the cumulative contribution from all of the network nodes upstream in the supply chain plus the contribution occurring at that node. Note that the reference flows do not necessarily represent material or energy balances for the pork functional unit, and therefore may not sum to the value of the reference flow of the receiving process.

Table 8 presents a list of the node names used in the network diagrams along with a definition describing the materials or process which are encompassed by that node. Tables B-1 and B-2 in Appendix B present a list of the parameters used in the model to characterize the base case system.

3.2 Overall Cradle-to-Grave GHG emissions.

Figure 8 and present the breakdown of the domestic pork supply chain GHG emissions. In Figure 8, each major supply chain stage has been subdivided into the primary contributing activities. The categories presented capture the supply chain activities that are unique to each stage of the supply chain. The chemicals classification does not include fertilizers, which are accounted for in the feed bar. The electricity shown at each level is the direct electrical contribution from that phase, thus electricity

Table 8 Unit Process Names and Descriptions for Network Diagrams

Cooking	Includes energy for oven preheat and cooking
Corn Feed	Combination of feed produced in different regions
Corn Grain	Production of crops (region specific)
DDGs	Dry Distillers Grains – includes allocation from ethanol production
Deep Pit	Includes emissions associated with deep pit manure management system
Electricity	Includes fuel mix, production, and distribution
Finish Barn	Includes Nursery and Finish barn operations
In Home	Includes transport from retail, in-home electricity for refrigeration and cooking burden
Lagoon	Includes emissions associated with lagoon manure management system
Natural Gas	Production, delivery, and combustion
Nitrogen	Natural mix of nitrogen fertilizer production
Overall	Cradle to grave; top level process
Processing	Includes all processes from farm gate to preparation of carcass for packaging
Packaging	Includes preparation of meat cuts and packaging on Styrofoam boat
Refrigerants	Includes production and fugitive emissions
Retail	Includes electricity for refrigeration, a share of store overhead electricity, and fugitive refrigerant emissions
Sow Barn	Includes facilities used for breeding, gestation, and lactation
Soy Meal	Includes processing of soybeans to oil and meal co-products
Soybeans	On-farm production of soybeans

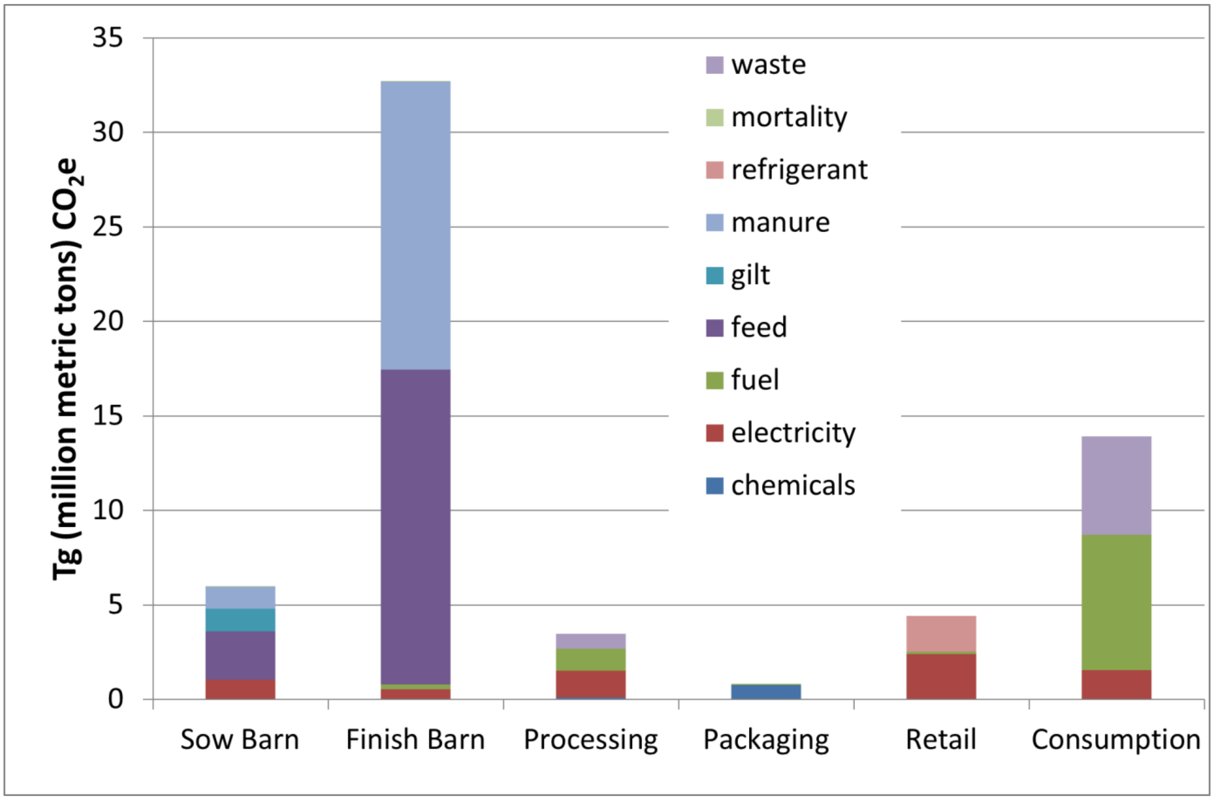

Figure 8. Cumulative GHG emissions associated with consumption of pork in the US. The legend entries are discussed in the text. The estimates in this analysis do not include GHG emissions from pork destined for overseas consumption or food service industry emissions.

for crop irrigation is included in the feed bar. For each barn phase shown, the manure management is the largest single contributor. In combination with Figure 9, it is apparent that much of the remaining contribution is associated with production of the animal's rations. Piglets are not included (contrast with Figure 1) as s separate bar in the finish barn as that is the simply the contribution of the sow barn.

The primary contribution from retail and home consumption is associated with electricity used for refrigeration, with some loss of refrigerants at retail; in addition, the waste emission at consumption includes an estimate of the methane released from landfill disposal of spoiled and plate waste meat. Because it is a legal requirement that refrigerants be captured from disposed household refrigerators, we have assumed that there is no significant GHG emissions associated with end of life appliance disposal.

In this analysis, we have not included weight loss on cooking, which can range between 20 to 30 percent due to a combination of water evaporation and loss of fat[28,29]. The USDA ERS is in the process of revising, from 39% to 29%, the consumer phase loss of pork due to the combination of cooking weight loss, spoilage, and plate loss (cooked, but discarded)[30]. Based on the proposed revision to consumer waste rates and the fact that weight loss during cooking does not induce additional production in the supply chain, we have used an estimated value of 10% for consumer phase waste. The overall cumulative GHG emissions for consumption of one 4-oz serving of US domestic pork based on reported manure management practices and accounting for an assumed 10% waste of product by consumers is 2.48 lb CO_2e. This model assumes a gas oven is used for cooking in the home; if in-home cooking is by an electric oven, the overall impact increases to 2.54 lb CO_2e per 4oz serving.

3.3 Scenario Analysis:

A series of scenarios are presented with alternate LCA models. The purpose of these alternate models used to highlight the impact that some choices have on results of the carbon footprint. These scenarios are focused on ration and manure management options at the live animal production phase of the supply chain. Scenarios for the post-farm supply chain are also presented. In addition to scenario testing, we conducted a sensitivity analysis.

The sensitivity of results to the main model parameters can be analyzed by adjusting parameters up and down 10 percent and observing the change in the model result. Thus, the sensitivity of the LCA to the most important input parameters can be evaluated.[32] These analyses can be used to target data collection, identify sources of improvement in process or analytical resolution, and to validate structures of LCAs. Sensitivity analysis is important for conducting a consistency check on the model/LCA.

3.3.1 Animal Rations

Biofuels are a significant factor in US agriculture, and corn ethanol is a particularly important contributor of distiller's grains to animal husbandry. Although at present, only approximately 1% of the distillers grains produced in the United States annually are fed to swine, the nutrient characteristics are favorable and the usage of distiller's grains in the swine production industry is expected to increase in future[33]. Evaluation of the difference in carbon intensity of different rations is therefore important. As models that account for the manure characteristics with different rations are created, this will be an even more important area of study.

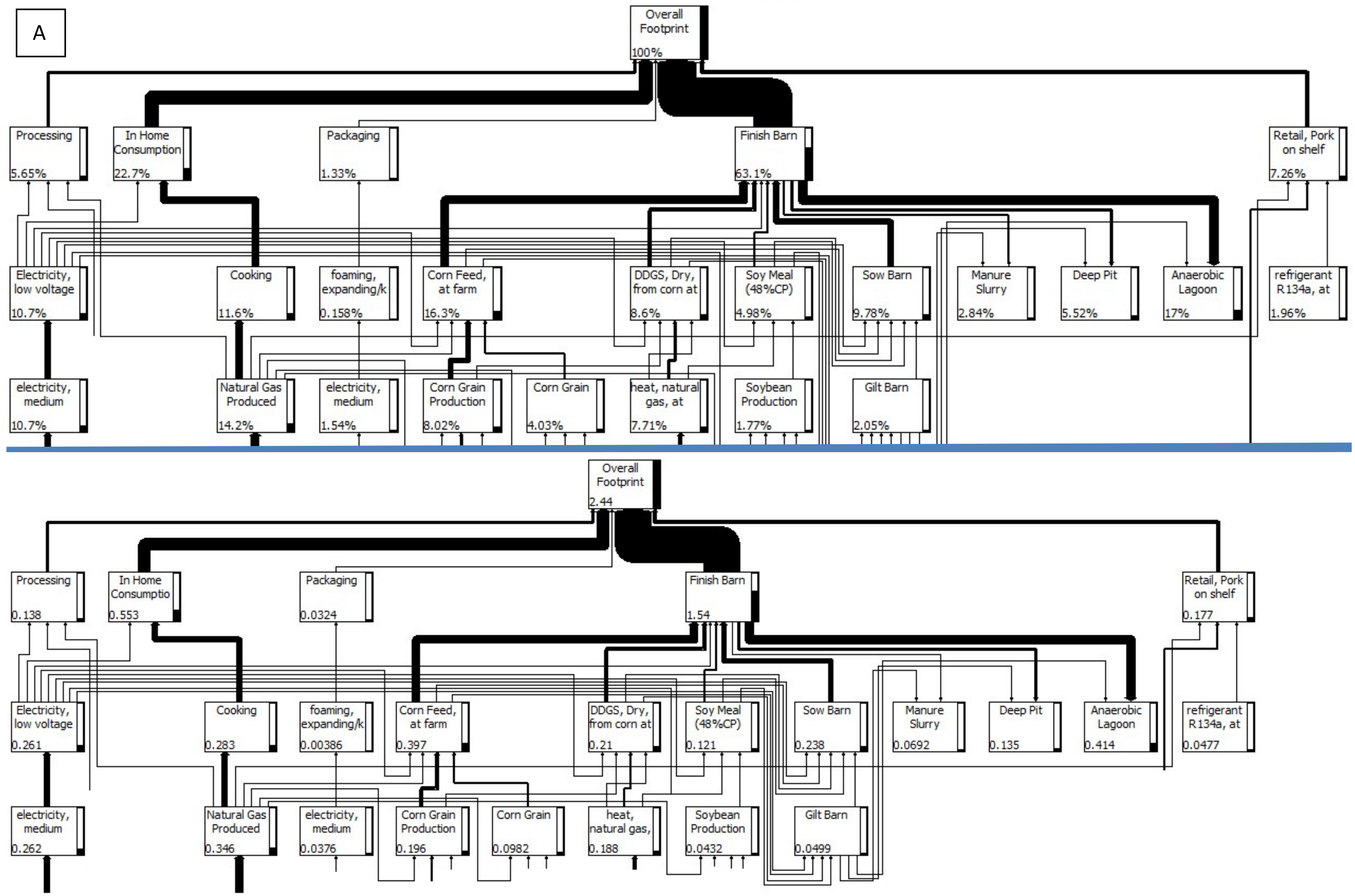

Figure 9. **A:** Percentage contribution of the major life cycle stages for consumption of pork. Analysis is based on the national average manure management profile, and assumes gas oven cooking. **B:** GHG emissions from the supply chain. Values in the lower left corner of each box are lbs CO_2e per 4oz serving prepared for consumption.

Figure 10 presents a comparison of rations which include or exclude distiller's grains. There is an approximately 6% reduction in the overall footprint when distiller's grains are not included in the ration. The additional processing of the corn to produce ethanol and DDGs results in DDGs having a larger GHG emissions profile than corn grain or soy meal. This is true for both wet and dry DDGs because approximately twice the mass of wet (~50% dry matter) DDGs is required to provide the same nutrient density as a ration using dry DDGs (~92% dry matter), and this approximately offsets the energy used for drying, that is, on a per lb (as-fed) basis, dry DDGs have double the footprint due to additional energy for drying, but only ½ the mass (as-fed) is necessary to provide the same nutritional content to the ration. UA swine specialists indicated that the majority of DDGs used are dry, rather than wet. The slightly larger bar for feed in the no-DDG case arises from an allocation decision in the model. Specifically, because of the economic allocation used at the distillery (98.3% allocation of the incoming corn to ethanol), the change from DDGs to a corn soy mixture results in higher footprint of those feeds.

3.3.2 Regional Analysis

Based on the information presented in Table 5 and region-specific Simapro simulations the

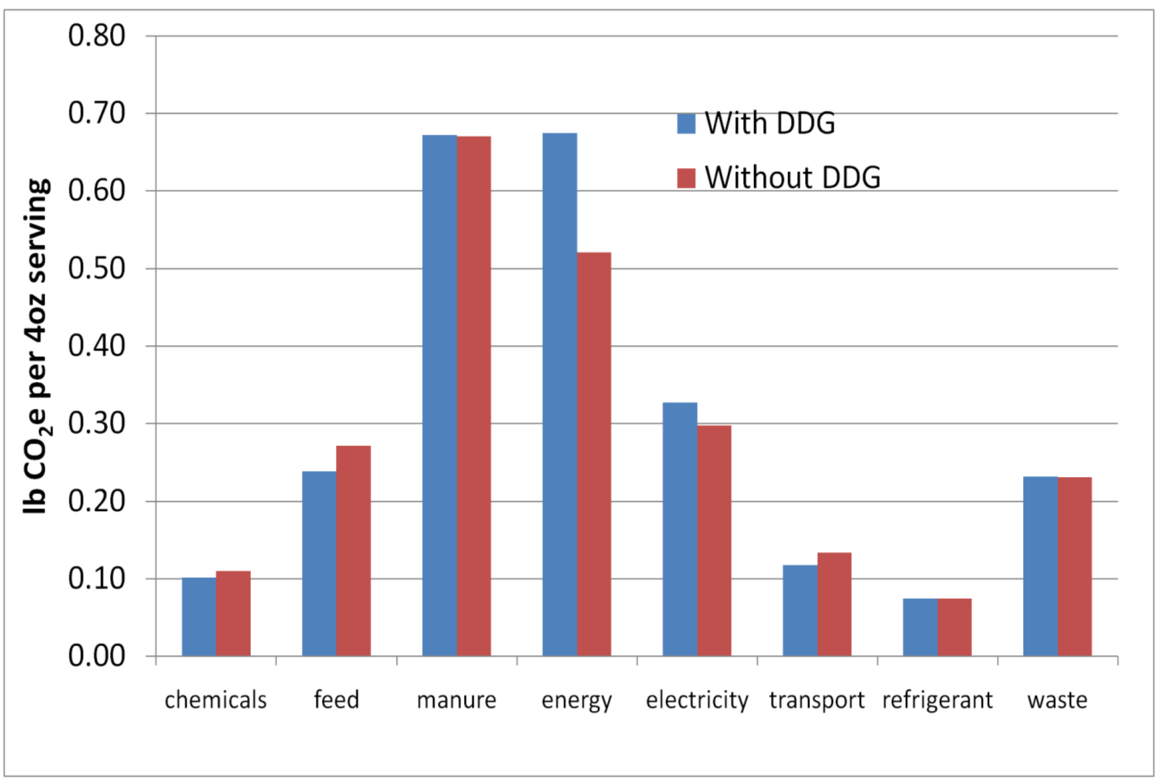

Figure 10 Comparison of lifecycle emissions with or without DDGs included in the ration. The rations were modeled to provide necessary energy and protein content. Most categories are similar except for energy consumption, which is larger when DDGs are included in the diet.

cumulative GHG emissions associated with live animal production (cradle to farm gate) by USDA production region are presented in Figure 11. Two factors are principally responsible for the differences between regions: first, and most important, is the number of animals sold to market in each region, and second is differences in the manure management profiles typical of the region. This is discussed in a later section.

Figure 12 presents a comparison of the five manure management practices reported by in the EPA GHG inventory[13]. In these comparisons, the only parameter changed was the type of manure management used for each of the barns modeled. The 'piglet' contribution is different between the scenarios as a result of the manure management. It is not surprising that anaerobic lagoons make a larger contribution to GHG emissions than other management options. It is interesting to note that the

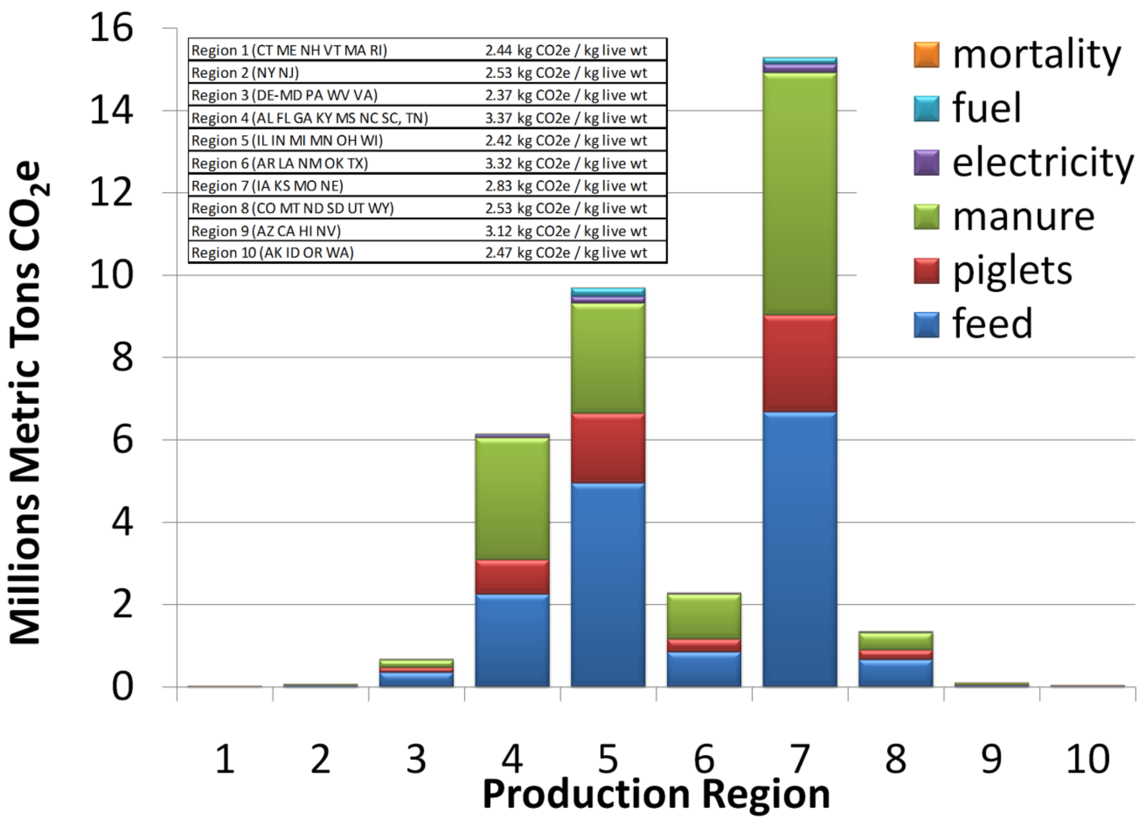

Figure 11. Cumulative metric tons of CO_2e associated with pork production in the U.S. These estimates are based on federally inspected units reported for the regions shown in the legend. The total boneless weight estimated from these data correlate very closely to the per capita pork consumption reported by the Economic Research Service (47 lb/person/year). This analysis does not account for the structure of the industry where sow operations are not necessarily near the nursery finish operations. For purposes of this analysis, the sow operation footprint was estimated as coming from the same region as the finished animals. The region and production weighted national average carbon footprint is 2.87 lb CO_2e per lb live weight at the farm gate (equivalent to 3.83 lb/lb dressed carcass or 5.9 lb CO_2e/lb boneless meat).

IPCC approach does not show a significant difference between pasture based manure management and deep pit systems.

Figure 13 presents results of a sensitivity study for several potentially important model parameters. These parameters and their values are defined in Table 9. We have evaluated DDG inclusion in the diet, as well as evaluation of the potential influence of fan efficiency, digestibility of the ration, feed to gain ration, mortality and cull rate. Note that cull rate is modeled through the proxy variable average number of litters per productive sow lifetime. Mortality management by incineration, composting, rendering and burial (in equal proportions) was included in the model. The 95% confidence band for the base case scenario is also shown. For the range of parameter values examined in this study, none of the changes shifted the farm-gate cumulative GHG emissions outside of the 95% confidence band for the base case.

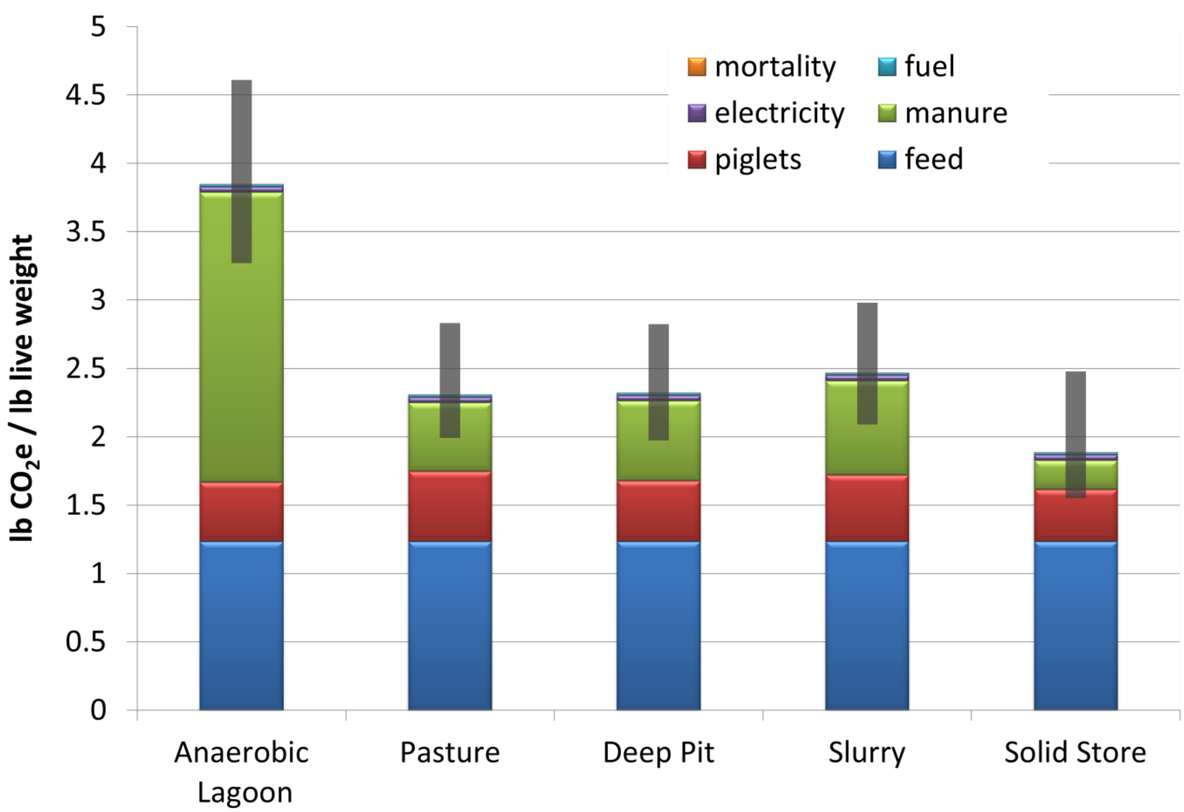

Figure 12. Comparison of manure management system choice on farm-gate cumulative GHG emissions. Note that the bar for piglets is different between the scenarios because of differences in manure management at the sow barn. The same manure management was selected for both the nursery-finish and sow barns. These scenarios all include DDGs in the ration. The vertical gray bars represent the 95% confidence interval based on 1500 Monte Carlo runs.

Table 9. Cradle to farm gate sensitivity parameters. Each row has parameters for a simulation. Shaded cells were the only parameter changed during each run (defined by a row).

Model Parameter / Scenario	Digestible Fraction	Conversion Efficiency	Finish /Sow Mortality	Live Piglets / litter	CFM / watt	Average Parities / Sow	CFM / sow	CFM / pig
Base Case	0.82	1	4	9.5	0.012	3.5	200	60
Low Digest	**0.738**	1	4	9.5	0.012	3.5	200	60
High F/G	0.82	1.05	4	9.5	0.012	3.5	200	60
Low F/G	0.82	0.95	4	9.5	0.012	3.5	200	60
High Mortality	0.82	1	10	9.5	0.012	3.5	200	60
Low Mortality	0.82	1	2	9.5	0.012	3.5	200	60
Low Piglet Mortality	0.82	1	4	10.45	0.012	3.5	200	60
High E Fan	0.82	1	4	9.5	0.0108	3.5	200	60
Low E Fan	0.82	1	4	9.5	0.0132	3.5	200	60
High Litter	0.82	1	4	9.5	0.012	3.85	200	60
Low Litter	0.82	1	4	9.5	0.012	3.15	200	60
Low Ventilation	0.82	1	4	9.5	0.012	3.5	180	54
High Ventilation	0.82	1	4	9.5	0.012	3.5	220	66

3.4 Post farm supply chain

We performed a similar scenario analysis for post-farm supply chain model parameters. These parameters are given in Table 10; as a test of sensitivity of the results to variation in the parameter values, we have taken a plus/minus range of 10% of the baseline value, and the results shown in Figure 14. The range of GHG emissions associated with the high and low parameter combinations remain within the 95% confidence interval estimate for the base case (mean). The trends identified in these scenarios suggest that while improvements are possible that significant reductions in the sector's overall GHG emissions will be derived from on-farm innovation. Again, the expected range of emissions is captured effectively by the 95% confidence bands that result from the Monte Carlo simulation.

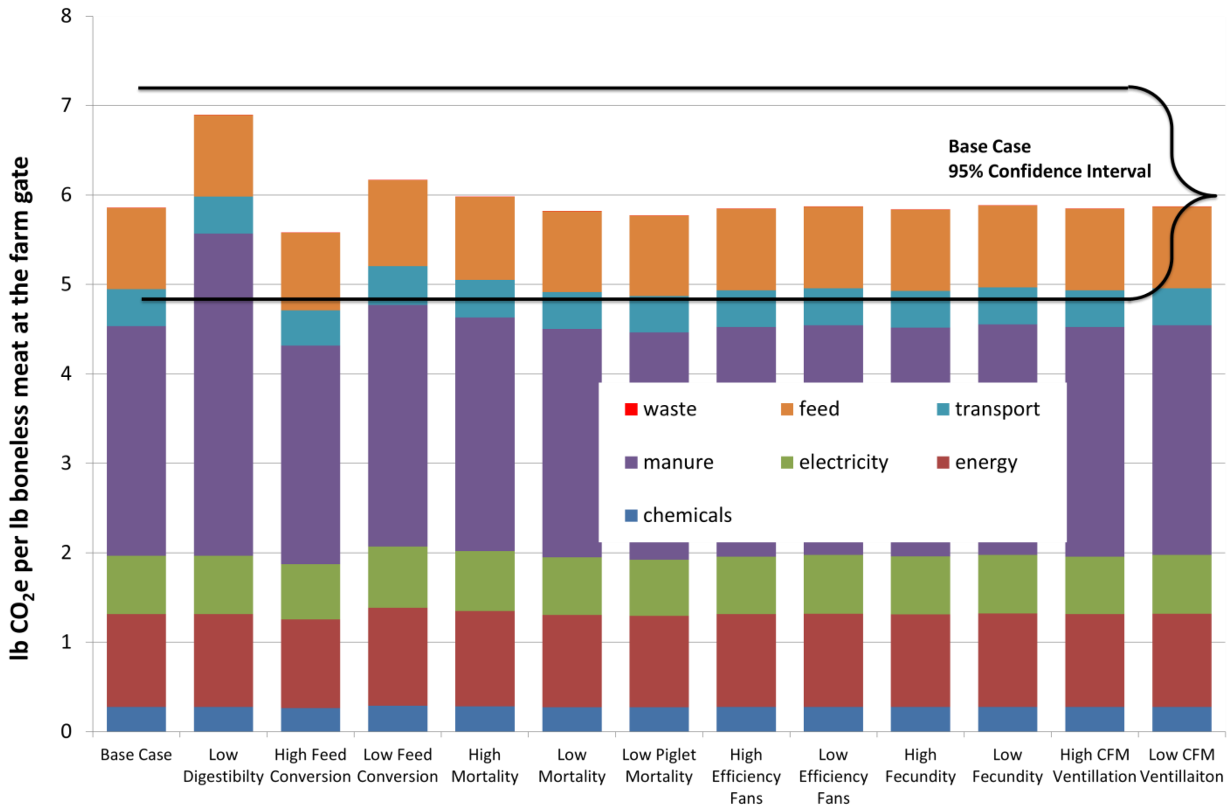

Figure 13. Sensitivity analysis for farm gate production. Reported on a boneless meat basis

3.4.1 Meat Processing

Figure 15 presents the details of the meat processing stage of the supply chain. The most significant contributors are natural gas and electricity. The diesel shown represents the fuel consumed in transport of live animals to the processing and packaging plant. Despite the relatively low contribution to the supply chain, there is still a large amount of energy and GHG emissions associated with processing and continued efforts to increase efficiency both for cost savings and reduction in GHG emissions are warranted.

Table 10. Parameters evaluated in post-farm gate scenario testing.

Scenario	Parameter Value		
	Low	Mean	High
Cooking	Gas	Gas	Electric
Allocation of consumer electricity	0.0117	0.013	0.0143
Annual consumer refrigeration electrical usage (kWh)	1213	1348	1483
In-home product waste	0.09	0.1	0.11
Retail loss fraction	0.0396	0.044	0.0484
Boneless fraction of carcass	0.7	0.65	0.6

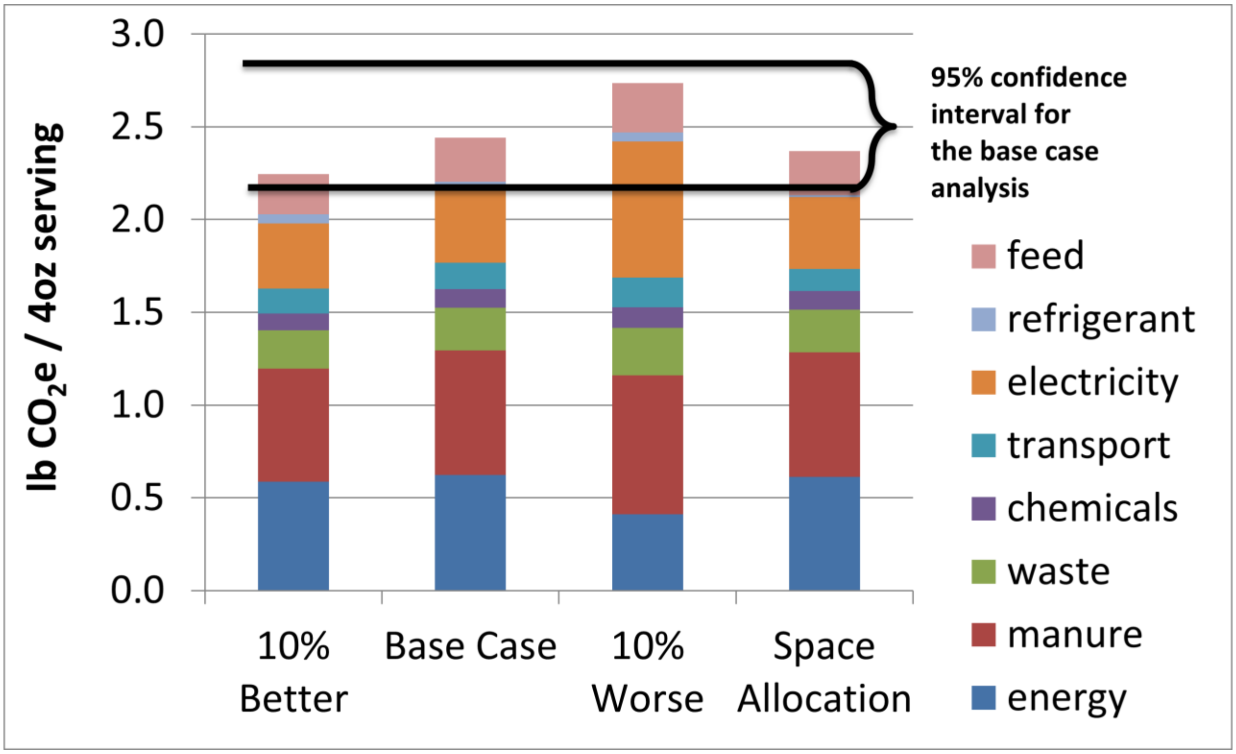

Figure 14. Post farm-gate sensitivity analysis. The most significant change is associated with the difference between gas and electric oven for cooking the meat. The last column is based on the assumption that retail and consumer phase allocation to pork follows the space occupied fraction of refrigerated and total store space for refrigeration burden (retail and consumer) and store overhead / consumer transport.

3.5 Retail Supermarkets

These stores sell a broad mix of food and a limited mix of general merchandise. They have a large land footprint (20,000 square feet or larger) and most use direct expansion refrigerant systems (EPA 2006)[34]. Common refrigerants are R-22, R-404A, and R-507A; for mixtures the composition of the mixture was used to determine the appropriate GWP[35]. These systems have a compressor that is housed separately from the refrigeration units, and the refrigerant is pumped in through a pipe network. This piping system is the source of most leaks, due to catastrophic events (e.g. a broken pipe). Supermarkets typically have 4,000 lbs of refrigerant in a system that leaks 18% annually. The USEPA GreenChill Program has collected and reported information regarding the sources and causes of refrigerant loss in supermarket systems[36].

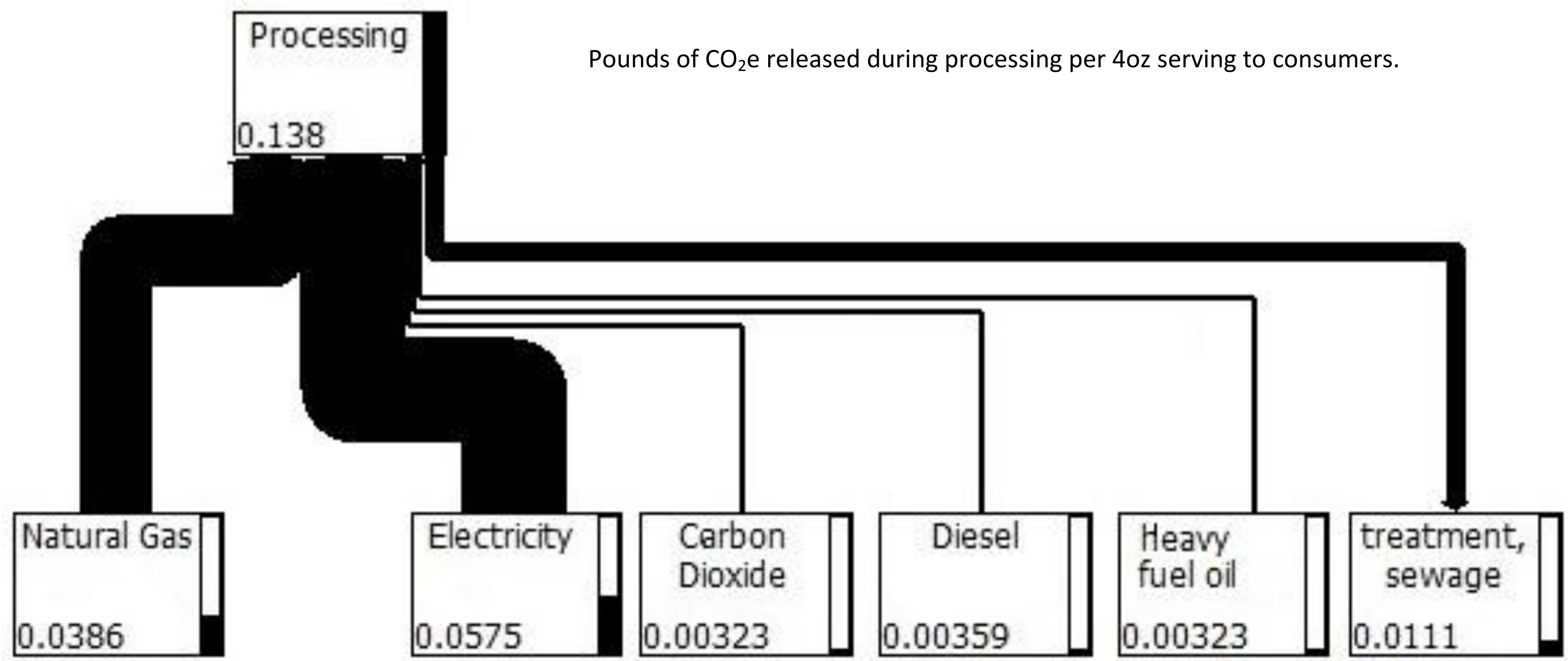

Figure 15. Gate-to-Gate impact of pork processing. The contribution is driven almost exclusively by natural gas and electricity. The overall footprint also includes diesel, gasoline, and fuel oil consumption as well as methane released from wastewater treatment facilities. The carbon dioxide in the third box represents the production burden from liquid carbon dioxide or dry ice. The difference (~0.021 lb CO_2e) between the sum of the 5 input boxes and the reported value for the dressed carcass leaving is the direct emissions of the purchased carbon dioxide or dry ice. Note that this diagram reference flow for processing is 4oz of meat prepared for consumption. The diesel consumption for this phase includes all transport of live animals from the farm gate to the processing facility.

4 Discussion and Interpretation

The ISO 14040 series of standards for conducting life cycle assessment require the inclusion of multiple impact assessment categories; therefore this study cannot be considered to be fully compliant with those standards. However other standards such as the PAS2050[37] are written specifically for carbon footprint analysis. To the extent possible, for single metric study, we have followed the appropriate international guidance in conducting this study. The results presented in this report provide some insight into the pork production industry and point to opportunities for reduction of GHG emissions; however, it should be stressed that it is not recommended that major decisions be made on the basis of a single environmental metric because there are frequently trade-offs with other impacts, for example increasing nitrogen retention in the manure management system will result in a larger land requirement for application of the treated manure.

The region and production weighted average carbon footprint is 2.87 lb CO_2e per lb live weight (equivalent to 3.83 lb/lb dressed carcass or 5.9 lb CO_2e/lb boneless meat) which places this cradle-to-farm gate GHG emissions estimate within the same range as similar studies performed on European pork production systems which range from 3 to 5 lb CO_2e per lb of dressed carcass (Table 11). As can be seen from Figure 12, for the deep pit manure management system, the burden per lb of live weight at the farm gate is approximately 2.32 lb CO_2e; which on a dressed carcass basis is equivalent to 3.1 lb CO_2e per lb dressed carcass (divide by the factor of 0.75, the dressed fraction of live weight) – this is at the lower end of the range from Table 11. Using the results from Figure 12 for anaerobic lagoon systems, the farm-gate footprint is significantly higher at 3.85 / 0.75 = 5.1 lb CO_2e/lb dressed carcass.

Table 11. Summary of EU pork production GWP data: Functional unit = 1kg carcass at farm gate.

	Global Warming Potential, lb CO_2e / lb carcass at farm gate	Reference
US Pork	3.8	This Study
Pork produced in Denmark	3.6	(Dalgaard et al., 2007)
Pork produced in UK	3.3	(Dalgaard et al., 2007)
Organic pork (Denmark)	3.8 – 4.3	(Halberg et al., 2007)
Pork produced in Sweden	2.6	Cited in (Dalgaard et al., 2007)
Pork produced in France	3.0*	(Basset-Mens and van der Werf, 2005) for GAP production
Pork produced in UK	5.6	(Williams et al., 2006)
Pork produced in Canada	3.1*	(Verge et al., 2009)

*value corrected from live weight to carcass

One somewhat surprising result of this analysis is that the contribution at processing and packaging is relatively low and that retail refrigeration and in home cooking are rather significant contributors to the overall carbon footprint. It is not surprising that transportation makes a relatively small contribution to the overall carbon footprint, despite its importance in the economics of the industry.

Dry distiller's grains are commonly used as a feed supplement in animal husbandry. Because the conversion of corn into ethanol is an energy intensive process, and because DDGS have an economic value for the ethanol manufacturer, they carry part of the manufacturing burden. The approach taken to allocate the burdens between the two primary products ethanol and the DDGS is important in the context of understanding and comparing LCA studies. The most common allocation approach used in the life cycle analysis literature is a mass allocation, which attributes approximately equal burdens to the ethanol and DDGS, the choice of allocation has a large impact on the reported GHG emissions. Soy meal, a byproduct of soybean processing, also requires an allocation of the processing impacts. Allocation choice is a significant factor in reporting LCA results because the value reported will be different, but only represents an accounting difference, and not a difference the underlying system. This highlights the importance of understanding LCA methodologies when comparing results from different studies.

4.1.1 Scenario and Sensitivity Analysis

Figure 13 shows the results of a comparison of several scenarios. The two factors that change the footprint the most are the change from deep pit to anaerobic lagoon, and the allocation choice for feed byproducts. In the former case, this highlights the potential opportunities for GHG reductions associated with technologies that capture or convert the methane from anaerobic lagoons. The allocation issue is discussed above. Based on available information, there is a significant contribution from consumer food preparation, with natural gas ovens favored slightly.

The observation that, for parameter ranges tested, all of the scenario results fall within the 95% confidence interval for the base case (both farm-gate and post-farm), suggests that there will be few technologies that will significantly reduce the pork production sector's GHG emissions alone. The possible exception is manure management (discussed below). Therefore, in efforts to reduce GHG emissions a suite of approaches each focused on an incremental improvement

Figure 16 shows the regional differences in on-farm emissions associated with manure management. The scenarios examined here are based on regional manure management profiles presented in Table 5. Table 12 presents parameters used in scenario analysis for regional effects. We evaluated the GHG emissions for regional profiles of manure management with an appropriate average annual temperature for each location. The main effects are associated with nitrous oxide and methane from the manure management systems as shown below in comparison of the base case for each region. The significantly larger emissions from Region 4 point to an opportunity for GHG emissions reductions associated with a shift away from anaerobic lagoons.

There are additional uncertainties in calculation of a carbon footprint associated with the values of emission factors used to predict the quantity of GHG emitted for a given management system. The most sensitive parameters are the fraction of volatile solids in the manure available for conversion to methane (B_0), and the rates of nitrogen volatilization from the manure management system. The ranges of these parameters are given in Table 12. The ranges selected are not intended to represent the full range of possible values, but represent, in combination, three cases that demonstrate the range of uncertainty associated with the IPCC emission factors.

Table 12. Parameter ranges for manure management systems sensitivity analysis

Sensitivity Parameter	Parameter function in model	Low	Mean	High
Methane Conversion Potential	Fraction of volatile solids that could be converted to methane	0.41	0.48	0.52
Lagoon volatilization	Fraction of N lost by volatilization	0.32	0.4	0.48
Pasture volatilization		0.24	0.3	0.36
Deep pit volatilization		0.2	0.25	0.3
Liquid slurry volatilization		0.41	0.48	0.52
Solid store volatilization		0.4	0.45	0.5
Lagoon leaching	Fraction of N lost by leaching into the ground	0.0025	0.005	0.01
Slurry leaching		0.0025	0.005	0.01
Deep pit leaching		0.0025	0.005	0.01
Pit direct N2O	Fraction of N converted directly to N2O	0.001	0.002	0.004
Slurry direct N2O		0.0025	0.005	0.01
Indirect N2O (volatilized)	Fraction of N converted to N_2O after loss from MMS	0.005	0.01	0.02
Indirect N2O (leached)		0.0075	0.0075	0.0075
Field Application	Fraction of N converted to N_2O after land application (inorganic fertilizer and plant residue)	0.004	0.0208	0.061

The sensitivity results show that Region 4 has larger GHG emissions, approximately 1 and ½ lb CO_2e per lb live weight compared to Regions 5 and 7 respectively. This is primarily driven by increased methane production as a result of higher average annual temperature and higher adoption rate of anaerobic lagoons for manure management. The large difference in the feed contribution to the footprint is associated, primarily, with the large uncertainty in the nitrous oxide emission rates associated with nitrogen fertilizer application (Table 12). The 95% confidence band for the base case is shown as a gray bar. In all three regions, the 95% confidence band is approximately the same as the expected range of emissions. In region 4, the feed and manure contributions are approximately equal, while in the other regions, feed is a more significant contributor to GHG emissions than manure management. This is the result of a larger proportion of anaerobic lagoons in region 4 combined with slightly lower average annual temperatures in the other two regions. The primary reason for differences in the feed contribution between scenarios in a region is the sensitivity to the N_2O emission factor for field application of nitrogen and crop residues.

4.2 Data Quality, Uncertainty and Reconciliation

4.2.1 Uncertainty in Input Variables

All data points have some uncertainty about them. The higher the uncertainty associated with an input variable, the less certain any results derived from that variable. Sources of uncertainty are a function of many facets of data, including reliability of measurements, sample size relative to total populations, representativeness of the sample, geographic variability, and many other characteristics. Sources of uncertainty can generally be categorized as variability and knowledge uncertainty.[38] Variability is the inherent noisiness of a system, the stochastic nature of a process. An example would be rainfall intensity; no matter how much you measure rainfall intensity, it will still vary over time and space because rainfall is inherently variable, though the characterization of the distribution of probable outcomes can be enhanced. Knowledge uncertainty is a measure of our ignorance of a system; it could be defined, given knowledge about the system, but those data are not available for the given analysis. Each type of uncertainty exists in any complex analysis, especially in LCA. The major sources of uncertainty in LCA are knowledge uncertainty associated with LCI data. Honest assessment of the impact of LCA requires quantifying both types of uncertainty in the output.

4.2.2 Monte Carlo Simulation

Propagation of uncertainty in mathematical models such as life cycle analyses are frequently performed using a process of iterative random sampling commonly called Monte Carlo simulation. The process is very simple in concept: a variable or set of variables in an equation are represented as distributions rather than discrete numbers. These distributions can be as simple as a uniform

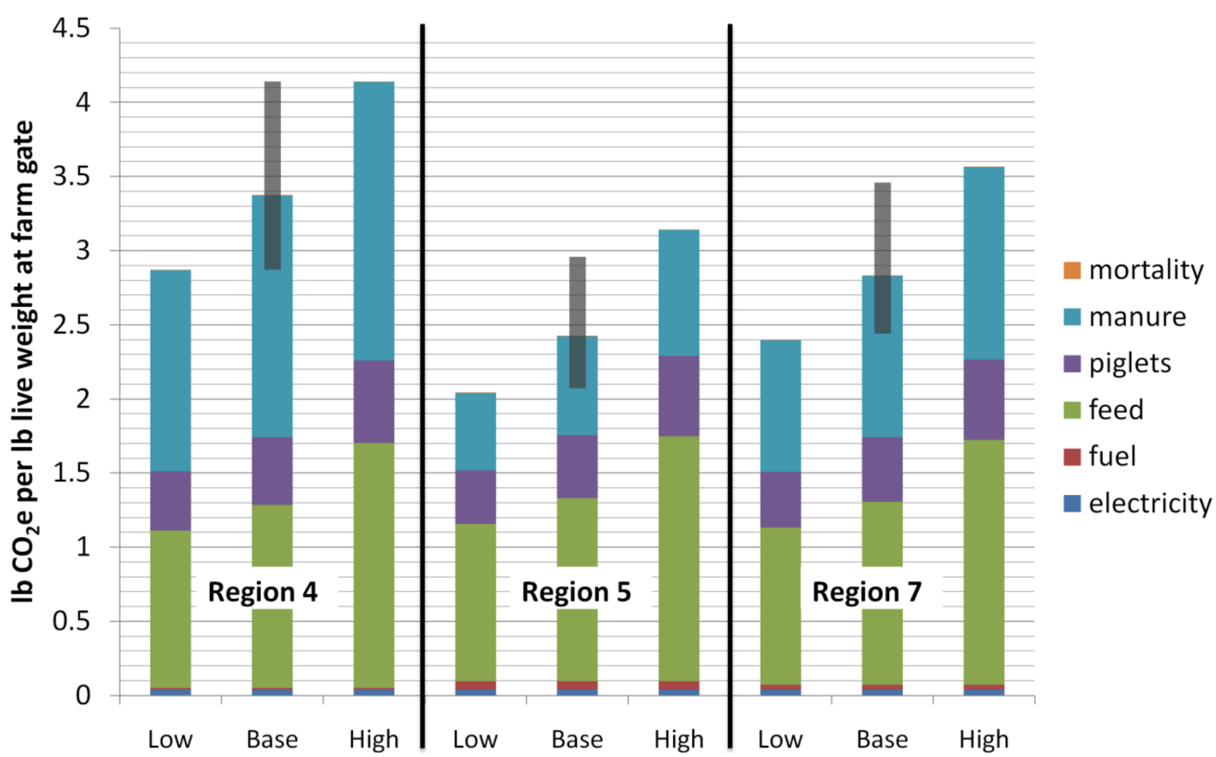

Figure 16. Comparison of regional differences and the effects of uncertainty in emission factors for manure management systems. Region 4 has a larger fraction of anaerobic lagoons than reported for regions 5 or 7, and thus has a markedly lager GHG emissions profile.

distribution, where the variable has an equal probability of being any number between a minimum and a maximum. They can be more complex such as a log-normal probability distribution, bounded by zero and positive infinity. Each time the model is executed (iteration) the software randomly selects from the assigned distribution for each variable (roles the dice, as it were), records the value, and calculates the outcome (results). This process can be repeated thousands of times to create a distribution of outputs rather than a single number. This allows the analyst to determine the probable outcome of a model or scenario, based upon a critical assessment of uncertainty about the inputs. Other techniques for propagation of uncertainty in LCA exist[39,40,41]; however, in this study Monte Carlo Simulation was used.

4.2.3 Assigning Distributions to Variables

Each of the model parameters as well as values of other input parameters has been assigned a probability density function which represents our best estimate of the potential range for that parameter. In addition to the basic or inherent variability in the system, we are following the EcoInvent protocol for assigning a pedigree to these data. The pedigree matrix considers factors such as the temporal and geographical relevance of the life cycle inventory data to the study at hand, the number of samples, the validity of the data with regard to verification as opposed to expert judgment, and the representativeness of the life cycle inventory data. Most of the distributions are considered to be log normal, which prevents selection of negative values during the Monte Carlo simulations, and has the added feature that the squared geometric standard deviation represents the 95% confidence band for the distribution. 1500 Monte Carlo simulation runs were performed to assess the confidence band of the estimated GHG emissions.

Variables in a model are assigned distributions based on a set of pre-determined criteria. SimaPro provides four distribution choices: Range (uniform), triangular, normal, and log-normal. These four distributions are adequate for propagation of knowledge uncertainty. A uniform distribution would be applied to a variable where only the minimum and maximum range of possible values is known. When a central tendency is known as well as the range, a triangular distribution can be applied. For data with more than five observations, a normal or log-normal distribution can be applied. If the data have a central tendency, normal distributions are appropriate. If there is an explicit lower bounded of zero (very common in natural resources data) a log-normal distribution should be applied. We have assigned uncertainty ranges to most variables; however there are some which have not been assigned. In particular, variables that have been parameterized to allow sensitivity analysis do not have distributions assigned as the Simapro software does not support this feature; the result of this limitation of the software is that the range of uncertainty in the final result is underestimated. In addition most of the allocation parameters are fixed because they are inter dependent and inaccurate simulations can result.

4.2.4 Data Quality Assessment

We have adopted the EcoInvent pedigree approach for assigning data quality indicators. Because most of the data for this project was derived from the literature, we have made estimated of the base uncertainty prior to application of the pedigree matrix. The uncertainty distributions are not based on extensive data collection, but on the best judgment of the research team and ranges observed in the literature.

4.2.5 Consistency assessment

There are some additional points regarding consistency of the modeling that should be pointed out. To the extent feasible we have used EcoInvent unit processes, used unit processes created at the University of Arkansas for other LCA projects (most of the crop production information) or created new unit processes specific to this project, however there were some instances where unit processes were modeled with economic input output (EIO) data. Differences in system boundary particularly between

EIO- and process-based models may result in some double counting of impacts. This is due to the fact that EIO models in essence have no specific boundary cut off criteria. For this study whey, used as a feed, was the only item for which EIO data were used. It contributes less than 1% to the feed contribution in the supply chain, and less than 0.3% for the entire supply chain as shown in Figure 17. The inclusion of this EIO data will not affect the study conclusions.

4.2.5.1 Infrastructure

Infrastructure has not been explicitly accounted in this analysis. We have done high-level calculations that would suggest that the contribution of infrastructure to the entire supply chain will be on the order of 2%. Because the primary purpose of the study commissioner was to evaluate operational characteristics of the supply chain, not potential impacts of capital expenditures, we have

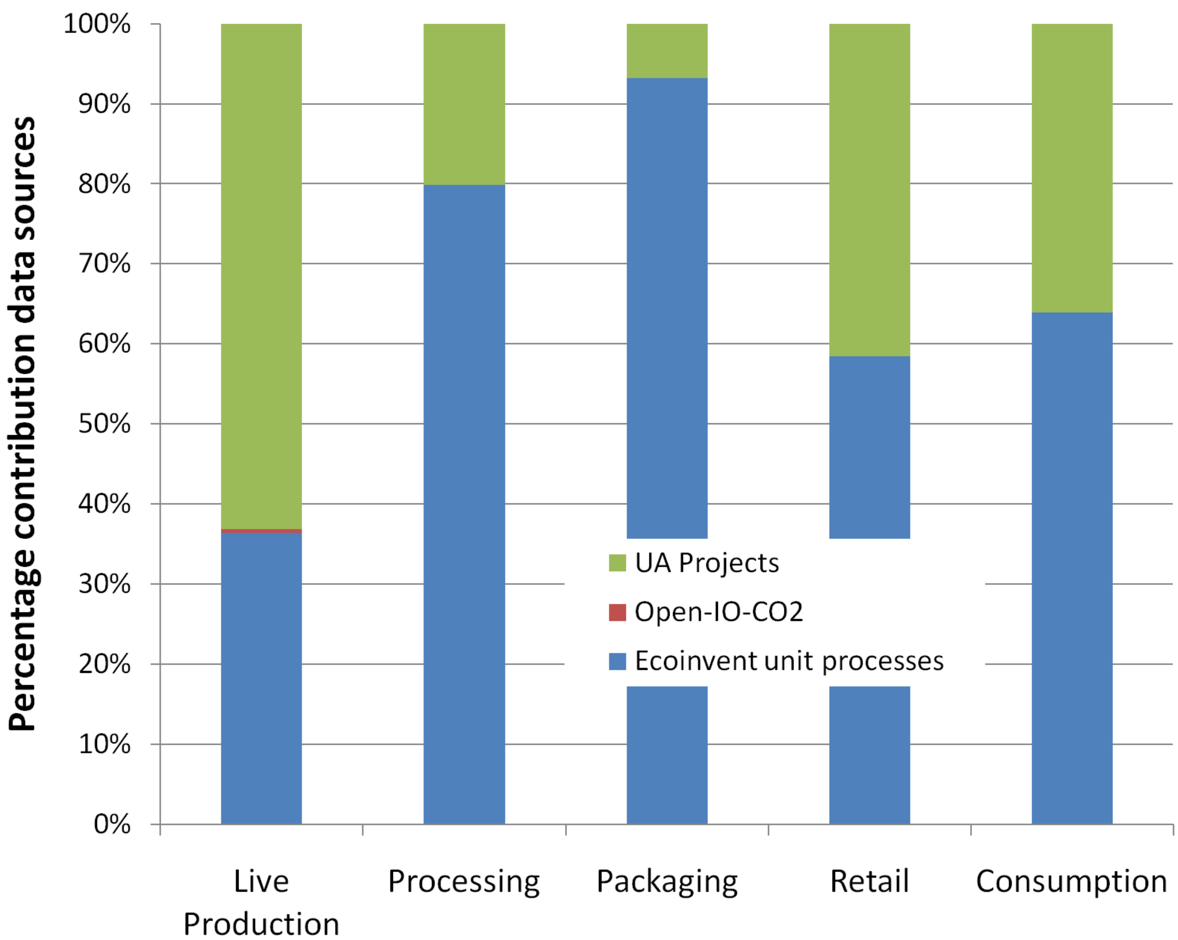

Figure 17. Database contribution to the carbon footprint for different supply stages. The green bar represents information collected or explicitly calculated for this project and includes, for example, emissions arising from crop residue. The red bar represents the contribution from economic input output data.

excluded infrastructure because it is relatively small (although potentially just above the cut off criterion). Thus the focus is to identify the opportunities for operational innovation. To ensure the greatest degree of consistency possible regarding infrastructure, all unit processes used in the SimaPro model were of type 'U' (unit) rather than type 'S' (system) so that when infrastructure processes are excluded from the analysis, they are excluded over the entire lifecycle, including deep background processes, compared to utilization of the integrated 'S' processes which were created with infrastructure included. Since the model was constructed in this manner, and because the background processes from the EcoInvent database do include infrastructure impacts, we performed a comparison with and without the background process infrastructure to estimate the effect of excluding infrastructure. The result of this analysis showed that including infrastructure impacts for background processes increases the footprint by approximately 2%. The overall conclusions of the study are unaffected by this because this impact is distributed throughout the supply chain, and the major impacts are not shifted.

One potential consequence of not including infrastructure is that economies of scale associated with large farming operations will not be completely captured because, in general, there are significant efficiencies in capital expenditures with increasing size of the facility. Because this analysis did not include the infrastructure burden, conclusions regarding the effect of farm size on the cumulative GHG emissions must be made cautiously.

4.2.5.2 Allocation

We have used different allocation procedures at different stages in the supply chain. For specific stages we have made every effort to apply the same allocation procedure uniformly to prevent bias. As an example, for feed by products like grain meal and distiller's grains we have applied an economic value allocation for each of the byproducts; for scenario analysis, we compared to a uniformly applied a mass allocation. In order to do this, for some products, we retrieved the multi-output process from the EcoInvent web site and modified the default allocation fractions.

4.3 Model Validation

The LCA model was created using the SimaPro software system for life cycle engineering, developed by Pre, The Netherlands. The EcoInvent database provides the life cycle inventory data for upstream burdens of most of the raw and process materials used as inputs. Our goal is to provide a transparent model for calculating the GHG emissions of the pork industry using a functional unit of 1 serving of pork consumed. All computational modules are documented with reference citations to external sources. Spreadsheet computations are documented with the supporting logic. All formulas have been checked by both the author of the module and at least one additional team member.

Because the intended audience of this study includes the general marketplace, an independent, third-party critical review was conducted. In order to prepare a defensible GHG emissions baseline and a transparent methodology that can be used to assess progress towards achieving a sustainable value chain in the pork industry, it is important to have a consensus regarding the sources and types of data used to develop the baseline, as well as general methodology.

5 Conclusions

In conclusion, the results of this scan analysis demonstrate that the mean value for cradle to farm gate production of pork in the US is within the range reported in the literature for pork produced elsewhere in the world, and is similar to other animal proteins. The results also show that both retail and in-home electricity use for refrigeration are non-trivial contributions to the overall footprint, while processing/packaging contributes a relatively smaller amount. Based on IPCC recommended calculations, the deep pit system is preferred to anaerobic lagoons due to reduced methane production.

The issue of allocation of burdens for feeds is an important one regarding reporting of carbon footprints, and it is recommended that a standard approach for handling agricultural byproducts like soybean meal and DDGS be agreed upon across the industries involved. This national scale analysis provides a baseline GHG emissions estimate against which the sector can benchmark future reductions.

Finally, the choice of manure management system is crucial in determining the carbon footprint. The contribution of on-farm energy consumption represents about 25% of the farm contribution for deep pit systems and only about 10% for anaerobic lagoon systems. The resolution of this scan does not allow us to highlight clear energy saving opportunities; however, efforts at energy conservation are simultaneously good for the environment and offer potential cost savings.

6 Literature Cited

[1] Dong, H., Mangino, J., Mcallister, T., Hatfield, J. L., Johnson, D., Lassey, K. R., et al. (2006) Chapter 10 emissions from livestock and manure management. 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

[2] American Society of Agricultural Engineers, (2005) ASAE D384.2 MAR2005. Manure Production and Characteristics.

[3] Purdue Pork Industry Handbook, (2009) Purdue University Extension Service, West Lafayette, IN

[4] Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, (2007) Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[5] Frank, Maxwell, and Thoma (2009) Greenhouse Gas Emissions and Global Warming Potential of the U.S. Swine Industry: Review of the Literature from a Life Cycle Perspective. www.npb.org

[6] Kansas State Swine Nutrition Guide. 2007, http://www.ksre.ksu.edu/library/lvstk2/mf2301.pdf

[7] H. H. Stein and G. C. Shurson. Board-Invited Review: The use and application of distillers dried grains with solubles in swine diets. J Anim Sci 2009 87: 1292-1303.

[8] USDA NASS, (2009) United States Department of Agriculture, National Agricultural Statistics Service, Agricultural Chemical Usage Summary; Crop Production Summary, http://www.nass.usda.gov/

[9] http://agmrc.org/renewable_energy/ethanol/ethanol__prices_trends_and_markets.cfm, Accessed March 2011

[10] United Soybean Board, (2009) Data update of soybean and soy feedstocks production and life cycle assessment of soy-based products and petroleum-based alternatives. Peer Reviewed Final Report. October, 2009.

[11] De Klein, C., Novoa, R. S. A., Ogle, S., Smith, K. A., Rochette, P., Wirth, T. C., et al. (2006) “CHAPTER 11 N_2O Emissions from Managed Soils and CO_2 Emissions from Lime and Urea Application” in 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC.

[12] American Society of Agricultural Engineers, (2005) ASAE D384.2 MAR2005 Manure Production and Characteristics.

[13] USEPA (2009), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008; Annex A, Table 182.

[14] West, T. O., & Six, J. (2006). Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. Climatic Change, 80(1-2), 25-41. doi: 10.1007/s10584-006-9173-8.

[15] Christopher, S., & Lal, R. (2007). Nitrogen Management Affects Carbon Sequestration in North American Cropland Soils. *Critical Reviews in Plant Sciences*, *26*(1), 45-64. doi: 10.1080/07352680601174830.

[16] Johnson, J. M., Franzluebbers, A. J., Weyers, S. L., & Reicosky, D. C. (2007). Agricultural opportunities to mitigate greenhouse gas emissions. *Environmental pollution (Barking, Essex : 1987)*, *150*(1), 107-24. doi: 10.1016/j.envpol.2007.06.030.

[17] West, T. O., & Marland, G. (2002). A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agriculture, Ecosystems & *Environment*, *91*(1-3), 217-232. doi: 10.1016/S0167-8809(01)00233-X.

[18] US Economic Census, Animal slaughter sector (31161), http://factfinder2.census.gov/

[19] Deru, M. and Torcellini, P., (2007) Source energy and emission factors for energy use in buildings, Technical Report NREL/TP-550-38617, National Renewable Energy Laboratory, June 2007.

[20] Genpak® (2011) polystyrene tray model number TR02P (7.8 lb/400 trays) http://www.genpak.com/product/processor-supermarket-trays/

[21] Elves, J., Ley, S. J. (1985) Absorbent pads United States Chicopee (New Brunswick, NJ) 4551377 http://www.freepatentsonline.com/4551377.html

[22] National Meat Case Study (2007) http://www.porkretail.org/filelibrary/Retail/NMCS_execSum100710small.pdf

[23] FMI, (2008) Supermarket Sales by Department – Percent of Total Supermarket Sales, http://www.fmi.org/docs/facts_figs/grocerydept.pdf

[24] Buzby, .J C., Wells,H.F., Axtman, B. and Mickey, J. (2009) Supermarket Loss Estimates for Fresh Fruit, Vegetables, Meat, Poultry, and Seafood and Their Use in the ERS Loss-Adjusted Food Availability Data. EIB-44, U.S. Dept. of Agriculture, Econ. Res. Serv. March 2009, http://www.ers.usda.gov/Publications/EIB44/EIB44.pdf

[25] USEPA (2005) Revised draft analysis of U.S. commercial supermarket refrigeration systems, U.S. EPA's Stratospheric Protection Division, November 30, 2005 http://www.epa.gov/Ozone/partnerships/greenchill/

[26] Energy Information Administration, Commercial Building Energy Consumption Survey, (2003) http://www.eia.doe.gov/

[27] Energy Star Grocery and Convenience Stores, Building Upgrade Manual, http://www.energystar.gov/ia/business/ EPA_BUM_CH11_Supermarkets.pdf

[28] Hamouz, F., Batenhorst, J, Driskell, J. and Mandigo, R. (1996) Impact of Cooking Method on Quality of Boneless Pork Loin Roasts. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1183&context=coopext_swine.

[29] Bertram, H. C., H. J. Andersen, A. H. Karlsson, P. Horn, J. Hedegaard, L. Nørgaard, and S. B. Engelsen (2003), Prediction of technological quality (cooking loss and Napole Yield) of pork based on fresh meat characteristics*, Meat Sci., 65*, 707-712.

[30] Muth, M. K., Karns, S.A., Nielsen, S.J. Buzby, J.C. and Wells, H.F. (2011). *Consumer-Level Food Loss Estimates and Their Use in the ERS Loss-Adjusted Food Availability Data*, TB-1927, U.S. Dept. of Agr., Econ. Res. Serv. January 2011.

[31] Cho, J.K., Park, S.C. and Chang, H.N. (1995) Biochemical methane potential and solid state anaerobic digestion of Korean food wastes, Bioresource Technology, 52:245-253

[32] Bjorklund, A.E. (2002) Survey to Improve Reliability in LCA. International Journal of LCA 7(2): 62-72.

[33] Distillers Grains In Livestock And Poultry Feeds (University of Minnesota) http://www.ddgs.umn.edu/overview.htm, accessed March 26, 2011

[34] USEPA (2006) Emissions from the U.S. Transportation Sector 1990 – 2003, Office of Transportation and Air Quality (6401A), EPA 420 R 06 003, March 2006

[35] http://www.refrigerants.com/refrigerants.htm

[36] Whitman, K., Thomas-Arkema, C., O'Shea, K., Strickland, N., Vogl, R., Cunningham, S., et al. (2009). GreenChill Best Practices Guideline Commercial Refrigeration Retrofits. Environmental Protection Agency. Washington, D.C.

[37] PAS 2050:2008 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services British Standards Institute ISBN 978 0 580 50978 0 http://www.bsigroup.com/upload/Standards%20&%20Publications/Energy/PAS2050.pdf

[38] Ling, C. W. (1993) Characterizing Uncertainty: A taxonomy and an analysis of extreme events. MS Thesis, Systems Engineering Department, University of Virginia, Charlottesville, VA.

[39] Heijungs, R., (2010) Sensitivity coefficients for matrix-based LCA, International Journal of Life Cycle Assessment, 15:511-520

[40] Heijungs R, Tan RR. Rigorous proof of fuzzy error propagation with matrix-based LCI. *The International Journal of Life Cycle Assessment*. 2010;15(9):1014-1019. Available at: http://www.springerlink.com/index/10.1007/s11367-010-0229-7 [Accessed December 10, 2010].

[41] Hong, J., Shaked, S., Rosenbaum, R.K., and Jolliet, O. (2010) Analytical uncertainty propagation in life cycle inventory and impact assessment: application to an automobile front panel. International Journal of Life Cycle Assessment 15:499-510.

Appendix A Comparison with other protein sources

As part of this project, the sponsor has requested that the results of this study be compared to published results for other protein rich foods. A comparison of existing life cycle assessments for other protein rich foods is presented in Table A 1. Aside from beef, the results from this study suggest that pork is comparable to other animal proteins. However, due to the potential for differences in methodology it is not advisable to make head-to-head comparisons on the basis of these reported results.

Table A 1. Reported GHG emissions associated with alternative animal protein sources.

Protein Source	Citation	lb CO_2e	Functional Unit	Study Location
Beef	Pelletier et al., 2010	14.8-19.2	lb live weight	Upper Midwestern US -
		11-14		includes SOC sequestration for pasture/grazing
Beef	Williams et al., 2006	15.6-25.3	lb dead weight	UK
Beef	Casey and Holden (2006)	11	lb live weight	Ireland
Beef	Cederberg and Darelius	17	lb meat	Sweden
Chicken	Pelletier 2008	1.395	lb live weight	US
Chicken	Williams et al., 2006	4.57-5.48	lb dead weight	UK
Chicken	Katajajuuri 2008	2.079	lb live weight	France
Salmon	Pelletier 2009	1.79-3.27	lb live weight	Norway, Chile, Canada, UK
Eggs	Moldenhurst et al. , 2006	3.9-4.6	lb egg	Netherlands

Appendix B. Model parameters used for sensitivity and scenario

Table B 2. Input parameters used for the base case scenario

Parameter	Value	Description
B_0	0.48	Fraction of VS available for conversion to methane
bgl_days	143	Breeding/Gestation/Lactation period (days)
meal_nf	1	lb/pig feed req'd per pig, nursery to finish, also used for gilt development
carcass_boneles	0.65	Carcass to boneless conversion
cfm_nf	60	cfm for ventilation in nursery-finish barn; Purdue handbook
cfm_sow	200	cfm for ventilation in sow barn; Purdue handbook
cfm_watts	0.012	Watts per cfm, assuming 0.1 inches water column pressure drop.
cons_alloc	0.013	(allocation of consumer refrigeration to pork products (approx. same as refrigeration space allocated to pork in supermarket refrigerated space - ignores items sold at ambient then refrigerated at home)
cons_pork	47.3	lbs pork consumed per capita in US (2005 ERS food availability data)
cons_refrig	1348	kWh/yr US household electricity used for refrigeration
cons_waste	0.1	Fraction of purchased meat disposed as waste
cooking	1	kWh to operate electric oven at 350 ^{o}F for 1 hour http://michaelbluejay.com/electricity/cooking.html
days_in_nf	165	Nursery to finish - (days)
digest	0.82	Digestibility of feed; est. ASABE manure handbook
EF3_pit	0.002	IPCC emission factor for direct N_20 from pit systems
EF3_slurry	0.005	IPCC emission factor for direct N_20 from slurry systems
EF4	0.01	IPCC emission factor for N_20-N from volatilized NH_3-N
EF5	0.0075	IPCC emission factor for indirect N_20 from leaching
fin_weight	268	Live weight, per pig, in lbs
hd_sow	1200	Number of sows in farrow - wean barn
heat_days	70	Heating days (dependent on average temperature)
leach_N_lagoon	0.005	IPCC fraction N lost through leaching
leach_N_pit	0.005	IPCC fraction N lost through leaching
leach_N_slurry	0.005	IPCC fraction N lost through leaching
live_carcass	0.75	Dressed carcass yield
N2O_residue	0.020821	kg N_2O per kg N in crop residue
npg_sow	9.5	Number of piglets per litter
num_house	3	Number of people consuming pork per household
litter	3.5	Average number of litters per sow
sow_barn_area	7.5	Area (in square feet) of barn per animal, sow barn
sow_weight	450	Live weight (in pounds), sow, at cull
suppl_nf	8	lb/pig feed req's per pig, nursery to finish, including gilt development
suppl_sow	6	lb/pig feed req's per pig, nursery to finish, including gilt development
vol_nh3_lagoon	0.4	Fraction of NH_3-N +NOx-N volatilized in lagoon mgmt systems
vol_nh3_pit	0.25	Fraction of NH_3-N +NOx-N volatilized in lagoon mgmt systems
vol_nh3_slurry	0.48	Fraction of NH_3-N +NOx-N volatilized in slurry mgt systems
vs_frac	0.8	Fraction of total manure solids that are volatile solids
weaned_weight	11	Weight of weaned piglet, entering nursery, in pounds
whey_nf	3	lb/pig feed requirement per pig, nursery to finish, also used for gilt development

Table B 3. Calculated parameters

hd_nf	hd_sow*npg_sow	Nursery/Finish barn entering head for one parity
heat_litter	0.250*24*14	supplemental heat per litter (14 days heat needed) kWh required per 250watts lamp (1 lamp per 2 sow)
light_sow	1.72*sow_barn_area*bgl_days* 24/1000	1.72watts/ft^2;
lpg_gpd	100/5000*hd_nf	Brumm, M.*
MCF_lagoon	-0.000527*T_avg^2+0.026993* T_avg+0.449*1.1	CH_4 conversion factor for lagoons manure systems IPCC Chap 10; Table 10A-7 10% correction factor to match Mangino (2001) which is the basis for the IPCC table.
MCF_pit_slurry	Exp(T_avg*0.0884)*0.0712	CH_4 conversion factor for liquid manure systems (both deep pit and liquid slurry systems) IPCC Table 10A-7
nf_barn_manure	hd_nf*(corn_nf+sbm_nf+ddgs_nf)* (1-digest)	dry matter in manure (lbs); all nursery and finish (N/F) pigs for one parity
nf_barn_N	5.11*2.205*hd_nf	pounds nitrogen excreted per finished animal litter; nursery + finish Table 18a ASABE
nf_barn_P	0.828*hd_nf*2.205	pounds phosphorus (same ref. as above)
sow_barn_manure	hd_sow*(corn_sow+sbm_sow+ ddgs_sow)*(1-digest)	dry matter in manure (pounds); all sows breeding, gestation, and lactation (b/g/l), one parity
sow_barn_N	hd_sow*bgl_days*0.117*2.205	0.117 kg/sow/day for 135 days b/g/l ASABE Table 18a converted to pounds
sow_barn_P	0.036*hd_sow*bgl_days*2.205	0.036 kg/sow/day for 135 days breeding, gestation, and lactation (b/g/l), ASABE Table 18a
vent_nf	cfm_nf*cfm_watts*days_in_nf* 24/1000/.6/.8	Electricity (in kWh) for ventilation for 160 days in nursery and finish barns, fan efficiency 60%, motor efficiency 80%, per nursery and finish (N/F) pig
vent_sow	cfm_sow*cfm_watts*bgl_days* 24/1000/.6/.8	Electricity (in kWh) for ventilation for 135 days in breeding, gestation, and lactation (b/g/l), fan efficiency 60%, motor efficiency 80%, per sow

*Brumm, M. 2008. Hog Barns Don't Come With Owner's Manuals. Pork Congress 2008 Producer Education Seminars, Minnesota Pork Producers Association. January 16-17

Appendix C Third party critical review

First Round Critical Review Life Cycle Greenhouse Gas Emissions Baseline Study for the U.S. Pork Industry

Reviewers: please insert your comments in the second column of the table below, Indicating section, paragraphs and page in the first column. Please use a new table cell for any new comment, to enable separate responses and action taken from authors to each individual comment. This Appendix includes two rounds of review comments.

	Comments and suggested changes by reviewers	Response from author & Implemented changes
2.1 General comments		
---	**General comment 1** Please specify in the report that reviewers had access to the model.	**Response:** **Action taken:** *Added with description of review process § 2*
---	**General comment 2** The study is intended for communication to third parties, but is not a comparative assertion. This confers some reporting requirements (ISO 14044, §5.2). The following seem to be missing for compliance: – description of cut-offs (not just the 1% rule used, but what this meant in the actual study, e.g., which elements were excluded, and also “de facto” exclusions such as infrastructure); – description of effect of cut-offs on results; – quantitative description of unit processes (not all available); – data quality assessment; – treatment of missing data (specifically, i.e., beyond statement that “sometimes” IO data were used); – description of critical review process.	**Response:** **Action taken:** *We have added a description of processes not included in the analysis as a result of the cut-off criterion in §3.1.7.* *We have also added §4.8 which includes the remaining information required.* *Description of review process included*

---	**General comment 3** Secondary data sources are not clear. It appears as if EcoInvent was given priority, but then US LCI is also mentioned. Also, it is stated that IO was used, and that the fraction of GWP stemming from IO data will be given, but this is not done. Please be explicit throughout the report as to which source is used. A statement regarding the problems associated with mixing data sources in one study should be included.	**Response:** **Action taken:** *We eliminated unit processes from the USLCI. The IO data contribution has been quantified and added to the report in § 2.3,§4.2.5, and Figure 17*
---	**General comment 4** Throughout the report results should be presented on a "per functional unit basis". Alternate units/metrics may also be presented for convenience.	**Response:** **Action taken:** *Where feasible this has been done and alternate units (SI) added parenthetically. For the farm-gate analysis, the results were left on a live weight basis.*
---	**General comment 5** It would be useful to include SI units. They could be secondary ( ) after US units now used.	**Response:** **Action taken:** *See above.*
---	**General comment 6** The assumed waste at different life cycle stages should be documented.	**Response:** **Action taken:** *Reference has been made to the ERS food availability data.*

Page & Section	Comments and suggested changes by reviewers	Response from author & Implemented changes
2.2 Detailed comments		
TITLE	**Comment:** The title of the document " …Carbon footprint study.." is more descriptive than the broader term LCA. Perhaps something combing the ideas would be even more descriptive without becoming too verbose; "…Life Cycle GWP of US Swine Production…"? This is a purely stylistic comment but it would be nice to begin to standardize the terminology for these types of study with the excellent series coming out of U Ark.	**Response:** **Action taken:** *Included 'Life Cycle' in the title.*
Section 1	**Comment:** the life cycle of production and processing facilities and transportation and field machinery do not appear to be included in the analysis. Is this because they were estimated to be below the cut-off? (See General Comment #2 above.)	**Response:** *These are infrastructure impacts, and infrastructure was explicitly excluded from this analysis. This decision was made in consultation with the project sponsor.* **Action taken:** *We have estimated that excluding all infrastructure results in an approximately 3% underestimation of the GHG emissions. A brief discussion is included in §4.8.6.2*
Section 3	**Comment:** It seems that you have the data available to calculate the energy used in the pork production chain. It would be nice to relate GHG emissions to fossil energy use. Although GWP is the primary goal of the study, energy use and the kind of energy used is interesting and important. This analysis would not need to be presented with the same sort of detail as GWP but would be interesting and useful.	**Response:** *We agree that this is interesting and useful.* **Action taken:** *We have not modified the report, as this is included in the process model for the swine farm production.*

Section 3.1.3 Figure 3	**Comment:** It would be helpful to see system boundaries and all products/coproducts crossing these boundaries (coproducts of abattoir and feed processing). Also, the term "energy inputs" for, e.g. pesticides, material inputs and refrigerants seems ill-chosen. Consider using ISO nomenclature (reference flows, intermediate flows, etc.).	**Response:** **Action taken:** *We have modified the system diagram to show the broad classes of co-products from the abattoir (figure 4) and feed processing stages of the system which are primarily meat/bone meal and tallow. These are used in a variety of downstream processes which are outside the system boundary.*
Section 3.1.3 Figure 3	**Comment:** "processing and transport" of crops has no fossil fuel inputs and no GHG emissions? Exports are shown but it is unclear how they are handled: inventoried as U.S. consumption? Ignored? Both of the comments in this box refer to the figure and the associated text. Please be clear as to how these were handled.	**Response:** *Explanation of exports was presented in §3.4. at the processing plant gate, the difference between export and domestic pork is 2-fold: different cut and different packaging. On a FU basis, the export stream has no effect on the result; at the resolution of this analysis, we did not have information specific to the impacts of different cuts of meat, and packaging of exported meat is out of the system boundary* **Action taken:** *The figure was updated to include inputs to processing and transport. Additional discussion of export added to §3.4*
Section 3.1.4	**Comment**: The functional unit definition is "prepared for consumption" but this is not clearly defined. Later (e.g., Section 4.2) there is discussion of different means of cooking. Text also describes eight 4-ounce servings, but it is unclear if they cut and then cooked, or cooked as larger piece of meat and THEN cut?	**Response:** *We believe that the reviewers are concerned that the energy requirements will be different depending on how the meat is prepared, and agree that this is the case. However, this work is not focused on the use phase, and the analysis of cooking options is included primarily to illustrate that there are measurable and significant emissions from this life cycle stage. Clearly additional research and analysis is necessary to achieve the resolution indicated by the comment.* **Action taken:** *For clarity, our assumption was that the meat was cooked and then cut, and this has been included in the discussion (§ 3.6)*

Section 3.1.5	**Comment**: It is stated that the ISO hierarchy was used, and yet the preferred approach to deal with multifunctional processes in this assessment is economic allocation (third and final option in ISO) for both feed processing by-products and rendering products. A mention that the actually chosen approach is the last option according to the ISO hierarchy should be included. A justification of why the preferred options were not possible is also required.	**Response:** **Action taken:** *Explanation added in §3.1.5*
Section 3.1.6	**Comment:** A discussion on how biogenic carbon (in CO2 and CH4) was dealt with is important in agricultural product LCA. (Suggest referring to or moving text from 3.3.3). Also, the justification for not adjusting the biogenic CH4 characterization factor (to account for initial uptake of CO2) should be given.	**Response:** *We are not clear why the reviewers believe an adjustment to the methane GWP factor is needed. In the analysis published by the IPCC the final degradation product of methane in the atmosphere is carbon dioxide, which is persistent in the atmosphere, and therefore a separate accounting of the sequestration at crop growth would result in an under counting of the GWP (that is the sequestered co2 ends back in the atmosphere, just like for corn ethanol)* **Action taken:** *We have expanded the discussion in §2.3.3 to address biogenic emissions more clearly.*
Section 3.1.6	**Comment:** This section refers only to CO2, CH4 and N2O, but introduction states inventory includes refrigerants.	**Response:** *Refrigerants are mentioned in this section, and were included in the analysis. The specific refrigerants used are available in the model unit processes. It is not clear what action the review panel expects based on this comment* **Action taken:** *None.*

Section 3.2, Figure 4	**Comment:** Replacement gilts are included in the graphic, but these are not mentioned in the text, and do not appear in the farm-gate GWP equation. They do, however, appear in the model to which the critical review team had access.	**Response:** **Action taken:** *Added explanation that the inputs in the equation include the replacement gilts, as modelled in the simapro model that was reviewed.*
Section 3.3	**Comment:** It is stated "A previously conducted literature review is used as the basis for much of the life cycle inventory data". Please cite and, if helpful, make available.	**Response:** **Action taken:** *Citation added. This document should be available on the NPB website.*
Section 3.3.1	**Comment:** It is stated "we have identified the most common feeds". Is what is being considered in the study an estimation of most common feeds, or an actual production-weighted average? If an estimation of most common feeds, then a measure of variability should be included in subsequent uncertainty calculations.	**Response:** *The rations used in the model are estimated from swine nutrition and typical growth rates. We have included effects of change in the diet associated with replacement of ddgs with corn and soy. Adding a PDF to the feed consumed without also changing the live weight production is similar to changing the feed conversion ratio; which confounds the results (that is the uncertainty in variability of the ration is potentially amplified when the animal weight is not also varied. Thus we have not added this analysis, but have indicated in the discussion that the uncertainty ranges are not fully reflective of the interdependent mechanisms due to the fact that this is not a dynamic model.* *The difference in the diet with and without DDG can be taken as an expected range of variation of the ration composition* **Action taken:** *We have added references to typical swine diets.*

Section 3.3.1.1	**Comment:** "Input data for fuels and electricity consumption for crop production were obtained from the technical literature, state agricultural extension services, the US Department of Energy, the USDA, and other academic institutions": Please cite.	**Response:** **Action taken:** *Citations added.*
Section 3.3.1.1	**Comments:** "The EcoInvent database was used to provide upstream information (i.e., production of fertilizer)": However, a review of the actual SimaPro model reveals that the ecoinvent database was used for more than only fertilizer production. Suggest replacing "i.e." with "e.g.".	**Response:** **Action taken:** *Corrected and clarified.*
Section 3.3.1.1	**Comments:** "Industry estimates" often cited. Please provide some details on how "industry estimates" were derived (interviews? With whom? Actual data collection templates or ad hoc telephone conversations?)	**Response:** **Action taken:** *Explanatory text added (e.g., §3.4) NDA in place for this project prevent disclosure of the specific companies that provided data.*
Section 3.3.1.1	**Comments:** It is not clear how the accounting was done for distillers grains. All of the drying energy is allocated to DDG. It seems that 98.6% of all other inputs were allocated to ethanol, leaving 1.4% allocated to DDG. Does this represent the economic value of the DDG v. ethanol? If economic allocation was used, provide justification for its use. Text is ambiguous. Please clarify.	**Response:** *The unit process for DDG was adapted directly from the multi output process, for US conditions, available from ecoinvent. The only modifications made were to create a new unit process for wet DDGs by removing the natural gas used for drying the DDGs (system separation per ISO). The majority of the remaining emissions were allocated economically by the EcoInvent center, and this was directly adopted for this scan level work.* **Action taken:**
Section 3.3.1.2	**Comments:** Is footnote in first sentence of section correct? The IPCC N2O emissions factors are found in Chapter 10 which covers livestock and manure management?	**Response:** *Chapter 11 covers field emissions and crop residues* **Action taken:** *The citation should be to chapter 11 of volume 4; corrected.*

Section 3.3.1.2	**Comments:** Given the importance of the N2O emissions and the uncertainly associated with the 1% estimate, please report how the variability of this input was handled in the sensitivity analysis. Variability due N2O, as seen in SimaPro model, seems very small.	**Response:** *Agreed.* **Action taken:** *We have modified the geometric standard deviation for the parameter N_2O_residue which is used to convert N application to N_2O emissions. Based on the ranges for direct and indirect N_2O emissions, we defined the GSD so that the maximum emission rate estimated (in which scenario only 40% of applied N is available for plant growth, which on a national scale represents extremely poor N management) fell at the 99^{th} percentile of the associated distribution. The revised report includes this additional uncertainty in the MCS and reported confidence ranges.*
Section 3.3.1.3	**Comments:** It is assumed that distiller's grains are used in all rations (although different amounts are considered). Is it the case that all or most swine are fed DDGs, and if so is there a reference to support it? Do you have data regarding what proportion of swine are fed DDGs?	**Response:** *DDGS use in the swine industry is a moving target. As more corn is converted to ethanol, DDGS production will increase and so will it's use in swine diets. Use is dictated by the farms relative location to an ethanol plant and cost of DDGS relative to corn. Subsequently not all producers have access to DDGS. To account for this, estimates of the carbon footprint were calculated for both scenarios.* **Action taken:**
Section 3.3.1.3	**Comments:** "30 finished pigs plus one sow": we calculate 3.5x9.5=33.25 pigs. Perhaps one is used as "sow replacement" (replacement gilts), but we still have 32.25 pigs, not 30. Please explain the discrepancy.	**Response:** **Action taken:** *The figure '30' corrected to the actual value used in the simapro model of 32.25*

Section 3.3.1.3	**Comments:** Some confusion exists around the mortality of sows. If sows are expected to produce 3.5 parities at 9.5 piglets/parity, then shouldn't the percentage sow mortality per (number of parities * piglets per parity) be 100% ? It is much lower in model.	**Response:** *Mortality refers only to those sows that are not sent to market, but whose carcass is disposed.* **Action taken:** *Additional explanation added in the text in §4.2*
Tables 1-4	**Comments:** Unit expressing feed rate is missing a unit: Est. feed, lb/sow per how much time? For Table 3-4, a "per life" figure is conceivable (about 2.8 lb ingested/lb gained). For sows (Tables 1 and 2), one would need to know if these values are for the average 3.5 parities	**Response:** **Action taken:** *Heading was updated to clarify.*
Section 3.3.2	**Comments:** Re. different manure management systems, the text indicates that "Each can be modeled separately." It would be more useful to indicate what was actually done in the study at this point. A review of the model indicates that each was indeed modelled separately.	**Response:** *Each system has a separate unit process in the model, and thus different scenarios with single systems can be simulated. For the national scale analysis, all of the management systems were included in proportion to the fraction of manure managed, by region (see Table 6).* **Action taken:** *We have added clarification to the discussion in this section* .
Section 3.3.2	**Comments:** The manure management of the "sow barn" accounts for manure from sows but not from piglets. How is this handled? Model and report are not clear.	**Response:** *The ASABE reference indicates that the sow manure estimate includes piglet manure.* **Action taken:** *Better documentation added to both.*
Section 3.3.2.1 p. 13	**Comments:** Something seems wrong with the first sentence …EF use the emissions in kilograms …Should it perhaps be …EF is the emissions in kilograms…	**Response:** **Action taken:** *Corrected.*

Section 3.3.3	**Comments:** The last sentence in this section is not strictly correct. While methane is a more potent GHG, it degrades in the atmosphere to less potent gasses (~CO2). The 25 factor is the 100 year cumulative GWP of methane as it is released (with a much higher multiplier) and as it degrades into less potent GHGs. Clarify assumption regarding plant fixation of CO2 versus release as methane and subsequent degradation into CO2. (Also, see comment above on Section 3.1.6).	**Response:** **Action taken:** *This was revised to clarify the role of biogenic methane.*
Section 3.4.2 (and Section 4.5.2)	**Comments:** A log normal distribution is a very flexible and useful, but is only appropriate when the variable is restricted to positive values or the result of the multiplication of two normally distributed variables. Is this the case for all variables included in the Monte Carlo analysis? Clarify which distributions were used, what parameters were chosen, and how parameters were chosen.	**Response:** *All of the material and energy flows in this model are positive-definite, and therefore we judged that log-normal distributions were most appropriate.* **Action taken:**
Section 3.4.2 and Section 4.5.2	**Comments:** A table that presents contribution and sensitivity results side-by-side is recommended to provide an overview of parameters contributing to overall uncertainty. Are the numbers in Tables 9 and 12 representative of the variability's assigned for the Monte Carlo simulation?	**Response:** **Action taken:** *We have modified most of the figures in the report to make clear which processes are contributing to the GHG emissions. The values in the tables are representative of the distributions used in the model. Some sensitivity analysis was restricted to evaluate, comparatively, the impacts of different variables.*
Section 3.4.3.1	**Comments:** Were the state production volumes (Table 6) used properly to allocate production to each interconnect region? From where were the data on electricity production (cradle-to-plug) taken? From a review of the Simapro model, it appears only Eastern	**Response:** *As the reviewers indicate, electricity is a relatively minor contributor to the footprint, and for consistency we modified the model to use the national average electricity mix.*

	electricity was used for all life cycle stages (Western set at 0, Texan not considered). Please address. Also, the regionalisation of electricity data was only done for foreground processes, i.e. the background ecoinvent processes all use default (i.e. mostly European) electricity. This should be clear in the report. Note that the reviewers are conscious that the impacts of this electricity use are minor and changing this aspect of the model would probably not change the outcome of the study.	**Action taken:** *Interconnect data replaced with national average primary energy mix for electricity production. The report has been modified to indicate this and to mention the reliance on background EU processes.*
Section 3.4.3.2	**Comments:** Provide source for both combustion and pre-combustion emissions.	**Response:** *This language was intended to be explanatory of the processes included by default in the Ecoinvent datasets for fuels consumed in industrial settings. We did not in fact, in the model, separate precombustion from combustion emissions.* **Action taken:** *We have re written this section to avoid the confusion introduced by separation of life cycle phases of the fuel.*
Section 3.4.3.3	**Comments:** What unit processes were used to represent transport, and was the load factor adapted?	**Response:** *We did not adapt the load factor. We used a combination of EUR3 transport and fleet average transport from the Ecoinvent database.* **Action taken:** *None.*
Section 3.4.3.4	**Comments:** Provide information in the report on data sources for packaging (reference flows and inventory data).	**Response:** **Action taken:** *Added*

Section 3.5	**Comments:** No retail inventory data is supplied in the report, so we cannot review the approach. A complete explanation of retail inventory data, allocation, etc. Is needed. Also, is there an assumption that there is no waste at retail level?	**Response:** **Action taken:** *We have expanded the explanation for this phase, and have added the ERS food availability estimate of 4.4% loss at retail to the model.*
Section 3.6	**Comments:** No data supplied and methods not described, so we cannot review approach (allocation of transport burdens to pork product, allocation of refrigeration at consumer and retail stages to pork product, waste at consumer and retail). Also, apparent contradiction with earlier text (source of energy for cooking: gas & electric vs. gas only).	**Response:** *These allocations were based on the same approach as taken in the fluid milk study.* **Action taken:** *We have extended this discussion to include the relevant data and methodology.*
Section 3.7	**Comments:** 100% landfill does not represent the US situation well: if the study assumes that the burdens from incineration of packaging (and consumer pork wastes?) would be <1%, then this should be clearly stated. Also, please mention which ecoinvent landfill UP was used (there are many available, with different impacts). Finally, CH4 emissions from the landfilling of consumer pork waste may not be negligible: were these considered?	**Response:** *Corrected.* **Action taken:** *We modified the split between incineration and landfilling to represent current estimates (14% incineration, and since there is no significant recycling of expanded polystyrene, we assumed 86% was disposed in landfills).* *We could not find literature specific to methane release from disposed meat; however, work on anaerobic digestion (§3.7)suggests an upper limit of 0.344 kg CH_4/kg disposed meat. We used this factor.*
Section 3.8	**Comments:** First mention of US LCI DB, adding to the lack of clarity on what background data were used where.	**Response:** *Reference to USLCI should have been deleted* **Action taken:** *Corrected.*

Section 3.8	**Comments:** Since readers will not have access to the computational model, the citations would be better placed in the actual report.	**Response:** *The majority of these are available in the literature review.* **Action taken:** *Added citation to literature review*
	It is confusing and inconsistent that the reader must do a division to obtain the results per the stated functional unit. If the functional unit is not actually used in the study, why not use kg CO2eq/kg boneless pork instead?	**Response:** *Agreed.* **Action taken:** *Except for gate-to-gate sections of the report (e.g., live weight at farm gate) we have changed to functional unit basis with parenthetical units in SI*
Section 4	**Comments:** The SimaPro model refers to sows in farrow/wean farms. These are not mentioned in the report, or at least not under this name. Are these the "Breeding/Gestation/Lactation" farms (also referred to as sow barn?) of Chapter 4 of the report or Nursery/Finish farms? Consistent nomenclature should be used throughout report and models.	**Response:** *Farrow/wean actually refers to a barn, not a farm. It is the same as breeding/gestation/lactation barn.* **Action taken:** *We have modified the terminology to be consistent across the model and report.*
Section 4.2	**Comments:** Review paragraph for clarity: "The overall cumulative GHG emissions for consumption of one 4-oz serving of US domestic pork using based on reported manure management practices and accounting for an estimated 10% waste of product by consumers 2.25 lb CO2e.. This model assumes gas oven cooking in the home; if in-home cooking is assumed an electric oven, the overall impact increases to 2.31 kg CO2e per 4oz serving. increases to 0.195 kg CO2e. In this analysis, we have not accounted for any weight loss on cooking. ." Also, note the mix-up in units (should say 2.31 lb CO2e, not kg).	**Response:** *Thank you.* **Action taken:** *Corrected §4.2*

Section 4.3.2	**Comments:** Results should be in terms of the functional unit. Figure 11: It would be good to see the efficiency numbers (e.g., kg Co2/kg live weight) for each region, perhaps in the legend?	**Response:** **Action taken:** *Added*
Section 4.4	**Comments:** Figure 14. Second column could be titled DDG Mass Allocation for clarity (or is this mass allocation for both DGG and soy?).	**Response:** *It is for both* **Action taken:** *Clarified.*
Section 4.5	**Comments:** "This study focused on a single environmental impact metric, GHG emissions, and as such cannot be considered to be completely ISO compliant." We suggest you add the qualifier that this study is not fully compliant as an LCA. The carbon footprint standards, when available from ISO and currently from PAS2050, do not require a full range of impact categories.	**Response:** **Action taken:** *We adopted these suggestions*
Section 4.5	**Comments:** This is the first time we have details on how the 95% confidence interval was determined. This should be explained (or cited) in previous sections referring to the 95% confidence interval.	**Response:** **Action taken:** *Citations to this section added in the document.*
Section 4.5.1	**Comments:** The sensitivity analysis is interesting, but information on how the high and low values were determined is required.	**Response:** **Action taken:** *Explanation has been added.*
Section 4.5.2	**Comments:** More references are needed in general. For example, section 4.5.2 Monte Carlo Analysis could benefit from reference to fill in detail of how distributional choices are made and methodology (e.g., Hong et al. 2010, Intl. J. LCA).	**Response:** **Action taken:** *Added explanation and citations to other methods*

Section 4.5.2	**Comments:** The 95% confidence interval is based on the use of lognormal distributions in Monte Carlo (again, were they all lognormal?), but the choice of the mean and variance of the underlying distributions were chosen how? The confidence interval reported is based on the assumption that the distributions accurately represent reality AND that no other important variables that are uncertain exist. More discussion and qualifications are necessary. The 95% confidence applies to the distribution as defined – and does not include uncertainty in the estimation of the distributional parameters. The attribution of uncertainty factors is not consistent. Most are based on the pedigree matrix, but some appear baseless (e.g. for refrigeration) and others are simply missing (when "calculations" are used in SimaPro, which would require authors to enter parameters in the equation in the parameter page and enter the uncertainty on each parameter individually). More importantly, the so-called "basic uncertainty" (or intrinsic variability) factors used in the model do not appear to reflect real-life variability of parameters. Although the actual results of the LCA are not affected by this, the uncertainty is (probably very importantly) underestimated	**Response:** *Some of the Ecoinvent datasets have uniform or normal distributions, but all distributions created for this project were log normal. The mean was taken as the best estimate we could find from the literature or from data provided specifically for this project from NPB or stakeholders. The industrial data is covered by non-disclosure agreement that does not allow release of the participating company names.* *We agree that the uncertainty analysis is not fully complete – there may be variables that we have not included that are important; however, we have made every effort to create a complete model, subject to the cut-off criteria specified in the goal and scope.* **Action taken:** *We have checked uncertainty attribution and added pedigree matrix where relevant. We have added discussion of the limitations of the uncertainty ranges reported due to the use of parameters in the calculations in the report.* *Without additional feedback, it is difficult to address the concern that 'basic uncertainty' factors do not reflect actual variability. All of the concerns raised in this context point to a lower than actual range for the 95% confidence band, and we have indicated this in the report; with regard to N_2O, specifically, we have increased the variance of the distribution significantly, and the current CI include this effect.*
Tables 10, 11	**Comments:** Include full units.	**Response:** *Most of table 10 is dimensionless* **Action taken:** *Units added.*

Section 4.5.6	**Comments:** Although you caution against making comparisons, you do claim that the pork GHG intensity estimated in this study is "comparable" to other animal proteins. The suggestion is that they are "roughly equivalent", yet Table 13 reports values that range from approximately an order of magnitude lower (Williams, eggs) to five times higher (Pelletier, beef) than the pork GHG intensity on a live weight basis (e.g., Fig 16). Is more interpretation warranted? Note that the critical review panel felt that it was outside its mandate to review this comparison as we have not reviewed the referenced studies.	**Response:** *We agree that additional interpretation is warranted.* **Action taken:** *This has been moved to an appendix as it is not strictly within the scope of the project; however, the sponsor has requested that this comparison be included. Additional discussion included in Appendix B*
Section 3.2	**Comments:** Justification/explanation of choice of finished weight is required. The finished weight used in the calculations is stated to be 122 kg, which converts to 268.4 lb. This means the finished weight used is the higher value in the range presented in Table 3 (250-270 lb), which underestimates (compared to situation if midpoint were used) the farm-gate burdens.	**Response:** *Table 3 headings do not refer to finished weight, but to the feeding regime. That is animals begin consuming the 'finisher III' diet at 250 lbs and continue till they reach market weight. The national average market weight from the NASS database is 268 lb.* **Action taken:** *None.*
Appendix A	**Comments:** list of "parameters used for sensitivity and scenario" and provides what appears to be the baseline value. How were the parameters in Table 9 (page 27) selected from this much longer list? How were the values in Table 9 chosen? What were the ranges of "high" and "low" values chosen for sensitivity analysis?	**Response:** *Appendix A does present the baseline values for parameters in the model* **Action taken:** *There are additional parameters used for sensitivity beyond those reported in Table 9 (See tables 10 and 12). Parameter values were chosen, based on expected ranges of the selected parameters,* *Sensitivity parameters for ammonia volatilization were taken as 20% deviation from the midpoint value in the IPCC methodology. The remaining values for sensitivity analysis (Table 12) were chosen to give a fourfold range about the IPCC midpoint value*

Second Round Critical Review Life Cycle Greenhouse Gas Emissions Baseline Study for the U.S. Pork Industry

	Comments and suggested changes by reviewers	Response from author & Implemented changes
Title	Consider changing 'Swine' to "Pork". Pork is the functional unit and most of the discussion uses the term Pork rather than Swine. Per the functional unit, the report addresses the production of pork – the flesh of a pig used as food – rather than the animal. The report conclusion section (§ 5) uses the word "pork" exclusively.	**Response:** **Action taken:** *We have made this replacement.*
Additional General Comment	Upon reviewing the revised report the panel came to recognize that the subject of this study is the full dressed carcass. This fact is implicit in Figure 2 as well as Table 7 that shows that the animal is divided into two categories: (1) meat; and (2) rendering and meat byproduct. However, it is not explicitly stated in the report that the subject is undifferntiated pork meat. Although the functional unit is "one 4 ounce serving of boneless pork", the only explicit mention of a specific type of pork meat product is the "2 pound tenderloin" mentioned as an example of meat preparation by the consumer. As this is among the more valuable cuts, economic allocation using more disaggregated data would have yielded a higher impact for tenderloin than for generic, average meat. The approach taken is appropriate for a scan study of this type, but **a statement should be included in § 2.1.3** that makes it clear that the study does not differentiate between different types of pork meat and that there is no attempt to account for inputs to processed pork products such as bacon,	**Response:** **Action taken:** *We have added this caveat to both section §2.1.2 (functional unit), and included more discussion in the interpretation section of the report.* *Regarding the variable allocation factor. The report simply states that fixed allocation factors were used, not that they could not be included in a Monte Carlo analysis. The allocation for distillers grains was calculated outside of SimaPro because individual line items (natural gas for drying) have different allocation factors, and SimaPro only allows a single allocation factor between coproducts for all of the activity flows in that unit process. Thus in a specific instance a Monte Carlo simulation is not possible without also manually manipulating an external spreadsheet for each run of the Monte Carlo simulation.* *With regard to the question about "sensitivity and*

	sausage, jerky, or smoked meats (or associated emissions and wastes). The sensitivity and uncertainty of this allocation factor, and the potential for misinterpretation by readers, warrants **a short discussion on this topic in the interpretation chapter**. Also, this uncertainty should be accounted for in the uncertainty analysis. Contrary to what the report states, it is possible to have variable allocation factors and to include these in a Monte Carlo analysis, although using a bounded probability distribution function, such as the uniform or triangular distribution, will help avoid inaccurate simulations (where e.g., more than 100% would be allocated to one coproduct and a negative burden calculated for the other).	*uncertainty of this allocation factor, and the potential misinterpretation by readers," there is no allocation factor which could be applied, as there is no distinction in the model whatsoever for different cuts of meat, though different kinds of processing for jerky or smoked meats, etc. while it is possible to include a variable allocation between boneless meat and rendering products, this allocation is not meaningful in the context of the reviewers comments here. By varying the meat to rendering product allocation ratio from 9 to 13%, the final impact of pork consumed varies from 9.90 to 9.92 kg of carbon dioxide equivalent per kilogram of pork consumed; thus relatively little additional uncertainty would be introduced by adding this parameter to Monte Carlo simulation.*
Re. Response to General comment 3	There is a reference to US LCI database remaining in the report (Section 2.7).	**Response:** **Action taken:** *Deleted.*
Re. Detailed comment on §3	Response is not clear, "this is included the process model for swine farm production". Please clarify what the process model for swine farm production is. Also this seems to imply that energy calculations are only available for the farm process and not the remainder of the chain. This does not seem to be the case as there is mention made in the report of energy use in the processing, retail and end-use sectors. Please clarify where an interested reader can find energy information.	**Response:** *The process model refers to a farm level simulation model created for this project that will be available through the National Pork Board. The model includes detailed estimates of fuel consumption for on-farm activities.* **Action taken:** *Energy usage is accounted across the supply chain. References 22-29 are the sources for post-farm energy consumption estimates.*

Re. Detailed comment on former Section 3.1.3/Figure 3 (now § 2.1.4)	Only the first of the two issues mentioned in the comment has been dealt with. We are left with the label "energy input" in the diagram for all inputs from the technosphere (colored key box in upper right). Inputs such as "water" and "fertilizer" are not energy.	**Response:** **Action taken:** *We have corrected the legend to indicate simply process inputs.*
Additional Detailed comment on former Section 3.1.3/Figure 3 (now § 2.1.4)	The report states in § 2.1.3 that Figure 2 (formerly Fig 3) is a schematic of the system boundaries of the study, and its legend describes it as portraying the "major inputs and outputs relevant to greenhouse gas emissions." However, the figure shows "bulk packing" and "export" which are not included in this study. We suggest that the legend be modified to make clear what the figure is meant to show and/or that these two blocks be given a different fill color than the other supply chain blocks and the figure legend makes clear that these activities are NOT within the system boundaries.	**Response:** *Good points.* **Action taken:** *Figure updated and description included in the caption. Color coding has been improved to show system boundaries more clearly.*
Re. detailed comment on Section 3.1.6 dealing with biogenic carbon	The added text in Section 2.3.3 (note - response mistakenly references 3.3.3) does not clearly distinguish between carbon stored in aboveground biomass and carbon accumulating in soil. The stability of production practices allows one to exclude the issue of carbon accumulating in soil. This said, the reviewers have no issue with the exclusion of carbon stored in aboveground biomass and reemitted as CO2 later in the pork life cycle insofar as emissions as methane and long-term carbon storage are appropriately dealt with. Regarding biogenic methane emissions, the reviewers agree with the authors' reasoning for not modifying the characterization factor. Regarding long-term storage of carbon (relevant for a fraction of pork waste sent to landfill), this does not seem to have been included. Since the inclusion of this long-term storage of carbon could not conceivably alter the conclusions of the report, it is suggested that this omission is simply mentioned in the report.	**Response:** **Action taken:** *We will correct reference to the proper section in the original response.* *We will also add a discussion that long term storage of carbon has not been accounted in this project in §2.3.3 as well as in §2.1.3*

Re. §3.3.1	The response is a bit unclear. Perhaps what you intended to say is that there are not a big differences in swine diets by region (e.g. compared to dairy?). Please clarify response.	**Response:** **Original comment:** "It is stated "we have identified the most common feeds". Is what is being considered in the study an estimation of most common feeds, or an actual production-weighted average? If an estimation of most common feeds, then a measure of variability should be included in subsequent uncertainty calculations." **Action taken:** *We used an estimated ration, not a production weighted ration. This comment relates to the composition of the ration which has an influence on the time in the barn and final weight of the finished animals. Because this LCA model is not structured to include indirect, and linked effects, we have not explicitly modelled the uncertainty associated with variation in ration. However, as the final weight is a stochastic variable in the MCS, a portion of this variability is in fact captured in the simulations with uncertain final animal weight.*
Re. §3.3.1.3	Although DDG feeding to swine is a 'moving target", it seems to be a very small moving target. I found reference to 1% and 11% of DDGs produced in the US fed to swine. The 1% figure seemed to imply a national average while the 11% seemed to imply an average in Iowa and MN where swine facilities are in close proximity to Ethanol plants. We suggest mention the fact that feeding DDGs to swine is done but represents a small fraction of the nationally aggregated diet at present, and that this percentage may increase in future.	**Response:** **Action taken:** *We have incorporated these suggestions into the document in § 3.3.*
NEW COMMENTS: §2.2	Figure 4: "9.5 weaned piglets per sow" should read "33.25 weaned piglets per sow" (9.5 figure is "per litter").	**Response:** **Action taken:** *Corrected*

§2.6	Transport from retail to home is included: there should be some description of how the impact of this transport, where one can assume that often full groceries will be transported, is allocated to pork.	**Response:** **Action taken:** *We have included more detail in the discussion (§2.5 and §3.4)*
§2.3	Reference to §4.8 is incorrect, should be to §4.2.5. Also, please consistently refer to economic input output data/databases as IO or EIO to minimize confusion.	**Response:** **Action taken:** *Corrected.*
§4	First sentence doesn't scan. Some words were dropped? The intent seems to be to state that LCA requires multiple performance metrics, while carbon footprint standards like PAS 2050 do not. As currently written it doesn't make sense.	**Response:** **Action taken:** *Rephrased*
§4.2.3	The report states that "variables that have been parameterized to allow sensitivity analysis do not have distributions assigned as the Simapro software does not support this feature". There is a quick work-around for this problem: one simply needs to add the uncertainty to the parameters themselves, in the "parameters" window. This is a simple process that we estimate can be completed in approximately 30 minutes for the parameters in question. It should be done and the Monte Carlo re-run.	**Response:** **Action taken:** *In fact, the majority of parameters for which a pdf is relevant did have assigned values, and thus the effect of uncertainty in parameter values is substantially included.*
§4.3	This section seems to be a straight cut and paste from a former project. The milk project is discussed, the functional unit is identified as a gallon of fluid milk consumed, and the wrong audience is identified (general market, rather than the "stakeholders in the swine industry value chain" mentioned in § 2.1.7).	**Response:** *Thanks.* **Action taken:** *Corrected.*