12-31-2015

A Life Cycle Analysis of Land Use in US Pork Production

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Recommended Citation

Thoma, G., Matlock, M., Putman, B., & Burek, J. (2015). A Life Cycle Analysis of Land Use in US Pork Production. *University of Arkansas Resiliency Center.* Retrieved from https://scholarworks.uark.edu/rescentfs/1

A Life Cycle Analysis of Land Use in US Pork Production

Comprehensive Report

pork checkoff

UofA
UNIVERSITY OF ARKANSAS
DIVISION OF AGRICULTURE

Center for Agricultural and Rural Sustainability
University of Arkansas • Division of Agriculture

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Glossary of Terms

Carbon Footprint	A measure of the cumulative greenhouse gas emissions associated with production of the functional unit of the system. It is reported in units of kg CO_2e (kg of carbon dioxide equivalents) and in some literature referred to as Global Warming Potential.
Functional Unit	Quantified performance of a product system for use as a reference unit (ISO 14040). The functional unit provides the basis for comparison of alternative products or services.
Global Warming Potential (GWP)	A common metric for all the gases that contribute to the radiative forcing which affect global temperatures. The units for GWP are kilograms of carbon dioxide equivalent (kg CO_{2e}). GWP may also refer to the characterization factors used to convert emissions of greenhouse gases to the equivalent emission of carbon dioxide.
Land Footprint	A measure of the land occupation required for production of the functional unit of 1 kg live swine at the farm gate
Life Cycle Assessment (LCA)	A comprehensive methodology for quantitatively analyzing potential environmental impacts associated with complex systems. LCA consists of four iterative phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation.
Life Cycle Impact Assessment	An evaluation of the potential environmental impacts associated with the product system. This phase involves characterization of LCI extraction and emissions, using a methodology to convert inventory flows to a common equivalent unit (e.g., greenhouse gas emissions in terms of carbon dioxide equivalents: kg CO_2e).
Life Cycle Inventory (LCI)	A collection of inputs and outputs (known as inventory flows or exchanges) associated with the product system of a LCA. Inventory flows may consist of water, energy, raw materials, intermediate products, and emissions.
Land Use/Occupation	The amount of land used, over a given period of time, to produce the functional unit. The units for land occupation are expressed as m^2a, or square meters annum. In this report, this is also referred to as the land footprint.
Water Use	A measure of the supply chain water used in production of the functional unit. It includes water for irrigation, drinking and cooling water for the animals as well as other water use in the background supply chain.

Executive Summary

The goal of this study was to analyze land use in the production of US pork using Life Cycle Assessment (LCA). LCA is a comprehensive methodology for quantitatively analyzing potential environmental impacts associated with complex systems. Identification of processes contributing to high environmental impacts often highlights opportunities for gains in efficiency, which can increase the profitability and sustainability of US pork.

The environmental impact category analyzed in this assessment was land use. After reviewing existing information regarding land use in agriculture and livestock production, analysis for US pork production was performed at two scales: cradle-to-grave and cradle-to-farm gate. The cradle-to-grave analysis provided a scan-level overview of land use associated with the production and consumption of lean pork at an aggregated national level. The cradle-to-farm gate analysis provided a more granular assessment of the land use required for live swine production, and evaluated the use of alternate ration formulation as a tool for reducing environmental impacts. This report summarizes the results of this project, which was divided into the following tasks:

Task 1: Review existing literature of land use in animal agriculture production

Task 2: Conduct a scan-level LCA of land use in the pork supply chain

Task 3: Conduct a detail-level LCA of live swine production for land use

Task 4: Complete final written reports.

Literature Review

The purpose of the literature review was to summarize the most current information and knowledge regarding the status of land use accounting in agriculture and livestock production. The literature review identified work reported by other researchers and organizations, nationally and internationally, and was used to guide the methods and help create the life cycle inventory (LCI) for tasks 2 and 3 of this study.

The majority of published pork production LCAs come from universities and consultants in the European Union. Only a few have been completed for pork production in the US, and those reporting land use reported their results in different ways. Using information obtained from the literature, as well as personal communication with authors, literature reported values were converted to the annualized land occupation in square meters associated with the production of 1 kg of live swine weight (m^2a/kg LW) in order to enable fair comparison of the reported results across assessments. For purposes of this work, fallow periods between crops were assigned to the crop so the land is considered to be occupied for the entire year for production of that crop. Pork production in the US was reported to range from 3.5 to 7.2 m^2a/kg LW (17.1 to 35.2 ft^2a/lb LW). Crop production was often cited as the primary driver of land occupation associated with swine production. Several of the studies reviewed, especially the international pork LCAs, were not explicit when reporting the type or location of land occupation; this is partially the result of commoditization of animal feeds where the original source is not tracked along the supply chain. This shortfall in information remains one of the major areas for improvement in the assessment of land use, and other impacts from crop production, by LCA of large-scale livestock production.

Scan-Level Life Cycle Assessment

The goal of this task was to quantify cradle-to-grave land occupation resulting from pork produced and consumed in the US at a national scale. National production was assessed for each of the 10 USDA pork producing regions (Figure ES.1). The functional unit chosen was four ounces of boneless pork prepared for consumption.

The land occupation required for production of 4oz of lean, boneless pork produced in the US for consumption was estimated to be 9.75 ft^2a (0.906 m^2a). The total amount of land used by the US pork industry for all pork consumed in the US was estimated at 15,000,000 acre*years. Land occupation varied by region of production due to the differences in climate and feed sourcing. Regions with cooler temperatures and/or higher yielding crops generally resulted in lower land occupation requirements. In cooler climates pigs tend to eat more food per day than in warmer climates, which shortens the production cycle due to a mild improvement in the feed conversion ratio.

Swine rations were by far the largest contributor, comprising over 96% of land use in the supply chain, followed by the swine farm, packaging, and then processing. Retail and consumption had a negligible contribution. 68% of the contribution from feed rations can be attributed to the grow/finish stage of production followed by 18% from sow barns and 14% from the nursery. The contribution from packaging was surprising, which was slightly less than that of the swine

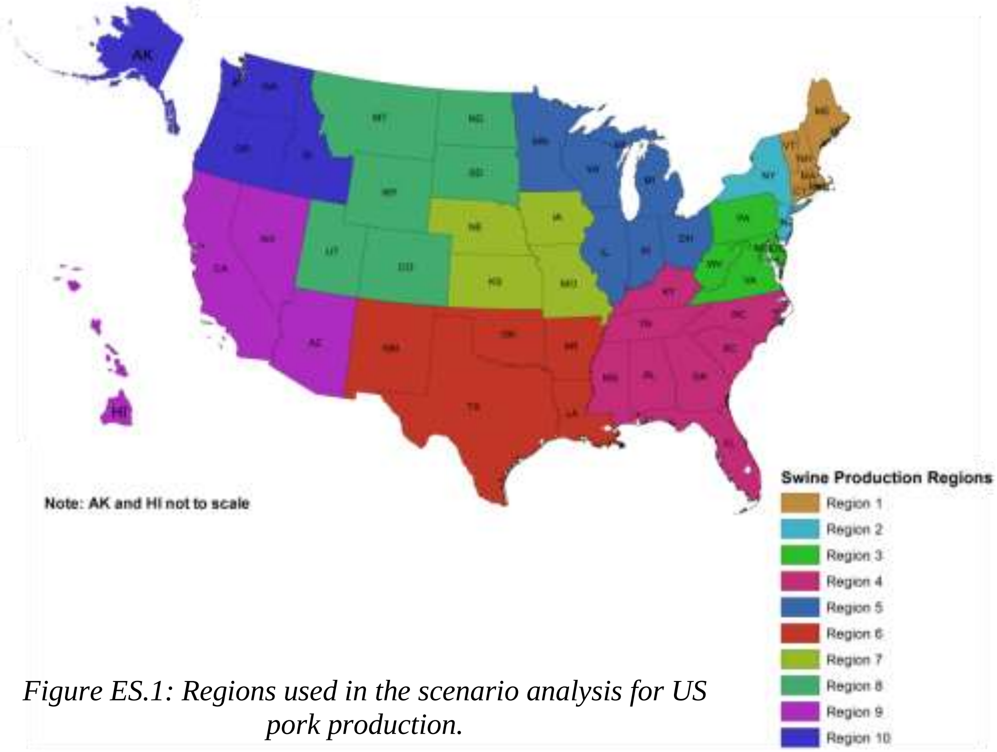

Figure ES.1: Regions used in the scenario analysis for US pork production.

farm. This was attributed to the absorbent pad. These pads are comprised of wood fibers, which have a significant land footprint due to the 25 to 35 year production cycle of agroforestry.

Detail-Level Life Cycle Assessment

The goal of this task was to conduct a detailed LCA of the US live swine production supply chain to quantify land use requirements and to assess the impact associated with various ration compositions. We also assess trade-offs between sustainability measures which arise as producers evaluate mitigation options related to ration composition. The functional unit was defined as one kilogram (2.2 pounds) of live swine at the farm gate, ready for transport to the abattoir. This assessment focused on the three highest producing USDA regions, which encompassed the Midwest (Regions 5 and 7) and the Southeast (Region 4), representing 86% of US market hog production (Figure ES.1).

The study showed that the average land occupation required to produce 1 pound of live swine in the US was 20.65 ft^2a (4.22 m^2a). This result is based on the use of a feed ration that was derived from the published literature and communication with industry experts in an effort to represent a national average swine ration, referred to as the baseline. Regional results were calculated assuming corn, DDGs, and soybean meal were sourced within each production region, excluding Region 4, which assumed 70% of the feed was a commodity average. Swine in Region 4 had the highest land occupation at 22.45 ft^2a/lb LW (4.59 m^2a/kg LW), followed by 20.23 ft^2a/lb LW (4.13 m^2a/kg LW) in Region 5 and 20.09 ft^2a/lb LW (4.11 m^2a/kg LW) in Region 7. Several factors influenced this result. First, regions 5 and 7 have higher yields than the commodity average for corn and soy. Higher yields naturally lead to a lower land requirement per kg live swine. Second, the climate in Region 4 tends to be warmer than that of the other two regions. In warmer climates pigs consume less food each day, which prolongs the time it takes to reach market weight. This resulted in a slightly worse feed conversion ratio than the other two regions and thus resulted in greater impacts associated with the functional unit.

In addition to the baseline diet, six diet scenarios were modeled to assess the impact of ration composition. A linear programming model was used to create four nutritionally complete and equivalent diets to evaluate ration manipulation strategies intended to lower cost, carbon footprint, water use, and land use. These hypothetical rations were intended to represent guidelines for developing realistic, sustainable and cost-effective pig diets that pig producers would be able to incorporate into their production system. While land use was the primary metric for this assessment, global warming potential – along with water use and feed cost – were included in the results in order to assess potential tradeoffs associated with formulating a feed ration around a single metric. Impacts associated with each diet were then compared to the baseline. All scenario diets showed reductions from the baseline in one or more categories ranging from 2% to 73%. However, each diet also resulted in greater impacts for at least one of the other category.

Two additional feed scenarios were adapted from experiments conducted by researchers from the UA in collaboration with Purdue and Virginia Tech. In these experiments, feeding trials were conducted to quantify the effects of substituting varying levels of synthetic amino acids to replace crude protein in diets for wean-to-finish facilities. The experimental diet that maximized the use of synthetic amino acids without sacrificing performance (labeled LCP) was incorporated into this study along with the experimental control diet. The LCP diet was shown to reduce land occupation and feed cost, but increase carbon footprint and water use versus the control diet. The relative results of all six scenario diets as compared to the baseline are presented in Figure ES.2.

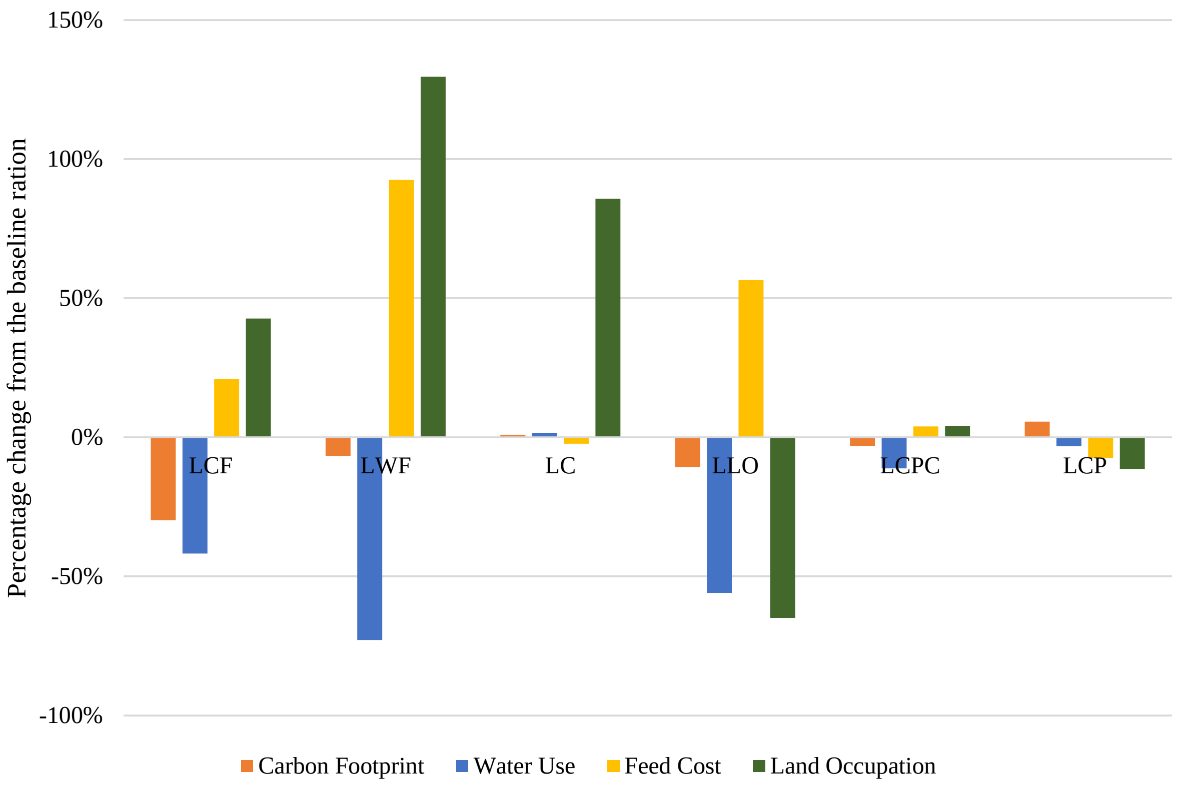

Figure ES.2: National average values for the diet scenarios and their associated impacts by category. Negative values represent a decrease in impact from the baseline ration. The four hypothetical diets are labeled Least Carbon Footprint (LCF), Least Cost (LC), Least Land Occupation (LLO), and Least Water Footprint (LWF). The two diets borrowed from the synthetic amino acid substitution experiments are labeled Least Crude Protein – Control (LCPC) and Least Crude Protein (LCP).

1 Literature Review

1.1 Introduction

Most of the ecosystem services upon which human enterprises depend come from the land. Land provides life support functions such as nutrient, carbon, and water cycling, as well as habitat for humans and all other life forms (Milà i Canals et al., 2007). Agricultural production, including cropland and grasslands, is a critical support function that currently occupies 43 percent of Earth's ice-free surface (Foley et al., 2011), making it the single largest human endeavor by land use on Earth. It is therefore critical to understand land use and how land management affects the potential for our land to continue to provide essential resources and ecosystem services.

The goal of this study is to quantify land use for US pork production using life cycle assessment (LCA). LCA is a method for quantitative analysis of impacts and risks associated with complex systems; these analyses support comparative assessments for management strategies. The life cycle of a product or process is composed of linked unit processes (e.g., feed production, swine farm, and pork processing), each with input and output flows of mass and energy (e.g., water consumption, land use, emission to air, water, soil). The collection of information that quantifies these flows is the Life Cycle Inventory (LCI). The LCI for land use for the US pork industry is from data from previous LCAs (Thoma et al., 2011, Thoma et al., 2013, Matlock et al., 2014), the Pig Production Environmental Footprint Calculator, peer-reviewed scientific data, and communication with industry experts. Data from this literature review will be incorporated into the LCI whenever appropriate.

1.1.1 Land use in LCA

Land use, for the purposes of LCA, refers to two types of processes: land occupation and land transformation. These processes have three characteristics that must be properly inventoried for use in LCA: 1) Surface area occupied, 2) Duration of the occupation or transformation process, and 3) The type of land occupied or transformed to and from. **Land occupation** is defined as "the use of a land area for a certain human-controlled purpose, assuming no intended transformation of the land properties during this use" (Milà i Canals et al. 2006). In general, it is possible to categorize land occupation as agricultural land occupation (crop production, etc.) and urban land occupation (industrial facility, commercial buildings, waste disposal, etc.) This type of land use is measured in units of area and time of occupation (i.e. m^2 year of cropland). Modeling this process represents the status quo; land occupation is generally considered part of the lifecycle inventory. **Land transformation** is an inventory of changes in the type of land occupation; defined as area of land (m^2) transformed from land use type x (e.g., forest) to land use type y (e.g., grassland). This implies the ecosystem services and resources provided by the parcel of land have changed. Due to the computational structure of LCA this is normally considered to occur at a point in time with the effects amortized over a period of 20 years (British Standards Institution (BSI) 2011)).

1.2 Review of Published LCAs

The purpose of the literature review is to summarize the most current information and knowledge regarding the status of accounting for land use in agriculture and livestock production. We have identified efforts conducted by other researchers and organizations, nationally and internationally, and are using their results to guide the methods and approach for a land use footprint for the National Pork Board (NPB) Board of Directors. We have used Google Scholar, ProQuest, and Web of Science to identify relevant published literature.

The majority of published pork production LCAs come from universities and consultants in the European Union (Dalgaard et al. 2007; Dalgaard 2007; Fry and Kingston 2009; Nguyen et al. 2012; Zhu and van Ierland 2004). Few LCAs have been completed for pork production in the US The available studies were reviewed to evaluate their land use methodology and identify hotspots to ensure appropriate data collection for this LCA. The majority of the existing pork LCAs in the peer-reviewed literature focused strictly on greenhouse gas emissions (Pelletier et al. 2007; Lammers et al. 2010; Ni et al. 2007; Wiedemann et al. 2010; Macleod et al. 2013; Weiss and Leip 2012; Vergé et al. 2008; Amon et al. 2007; Dalgaard 2007; Castellini et al. 2012). These reports are not discussed further because they did not provide information relevant to the land use inventory.

Several of the studies reviewed, especially the international pork LCAs, were not explicit when reporting the type or location of land occupation; this is partially the result of commoditization of animal feeds where the original source is not tracked along the supply chain. Mila i Canals et al. (2007) reported that this shortfall in information is one of the major areas for improvement in the assessment of land use by LCA. Land transformation information is also lacking in much of the reviewed literature, especially older assessments; however, it should be noted that the Ecoinvent lifecycle inventory database does include land use and transformation in the background supply chain for some unit processes. It is important for this study to acknowledge both land use processes which allows a more detailed assessment of land use impacts during the life cycle impact phase because the effects of land use can be regionally specific (Koellner et al. 2013) and are not exclusive to occupation alone.

1.2.1 North America

Data from a report on swine rations in Alberta, Canada was used to estimate a land occupation requirement (crops only, excluding production facility area) of 12.3 m^2a/kg live weight (LW) produced (SNC-LAVALIN Agro and Ciraig 2009), which is higher than most other reports. Pelletier et al. (2010) reported ecological footprints between 14.2 and 24 m^2a per kg LW for pigs produced with different practices in the US Upper Midwest. The ecological footprint characterizes, in ‘global equivalent hectares (gha)’, the total productive ecosystem area required to provide all the resources and greenhouse gas sinks necessary for the system under study. It combines characterization factors for land occupation (2.19 gha/ha cropland – indicating, from an ecological perspective, that the effect of land used for cropping has a slightly larger effect than the global average hectare) and GHG emissions (2.67 gha/kg CO_2 indicating that each kg CO_2 emitted requires 2.67 ha of land to act as a sink for the emission) (Frischknecht et al. 2007).

A characterization, or equivalency factor, is used by LCA modelers during the life cycle impact assessment (LCIA) phase as a multiplier for inventoried resources (in this case both direct land occupation and indirect land use needed to absorb emitted GHG) that indicate a different degree of impact of similar resources/emissions. The authors did not report the land occupation inventory and we have estimated the land occupation based on the literature values for characterization factors (Frischknecht et al. 2007). Based on Pelltier et. al. (2010) reported GHG emissions and ecological footprint, we estimate land occupation inventory of all relevant processes from cradle to farm gate for this study ranging from 3.5 to7.2 m^2a/kg LW[1]. This is dominated by the area required for crop production, but is reported to include all production phases to the farm gate.

Stone et al. (2012) report 147 m^2a/FU, where they define their functional unit as one head of swine produced from 29 to 118 kg – thus, for the grow-finish stage only, this is equivalent to 1.25 m^2a/kg LW. Because of the truncated system boundaries which exclude crop production, this is not comparable to other studies. Finally, Boyd and Cady (2012) reported 22.9 million acres for crop production needed for 30.4 billion pounds of LW (6.72 m^2a/kg LW) in 2009 based on estimated ration consumption and crop yield. Their study did not include other land occupation within the supply chain.

1.2.2 European Union

The US results aligned with six LCAs on pork production in the EU that addressed land use (Figure 1.1). Each considered ‘cradle to farm gate’ boundaries, although they differed slightly in functional unit. Therefore, reported results were converted to kilogram of live weight when necessary. de Vries and de Boer (2010) summarize several EU LCA studies and report land occupation ranging from 5.3 to 8 m^2/kg LW for swine compared to 9.8 to 16.5 m^2/kg LW for beef and 4 to 5.5 m^2/kg LW for chicken. All studies reviewed included on-farm land use and encompassed conventional production systems, as well as organic and/or free-range alternatives.

The European studies provide useful insights for performing an LCA of US pork production, although care must be taken when drawing conclusions from their findings. Figure 1.2 shows the differences in swine feed composition for different parts of the world. The makeup of swine feed is only one of the major differences between swine production in the US and elsewhere. For example, Stone et al. (2010) outlines five important distinctions between EU and US production:

1. Different genetic make-up of EU swine herd
2. Utilization of nontraditional (from a US perspective) feedstuff
3. Typically less-efficient ventilation systems
4. Differences in market weights as EU market pigs are generally lighter weight resulting in greater feed efficiency gains
5. Different manure management practices in the EU

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[1] $EF = EF_{direct} + EF_{CO2} = 2.19$ *(land occupation) + 2.67*(GHG emissions); substituting reported GHG emissions and EF leads to a calculation of land occupation.

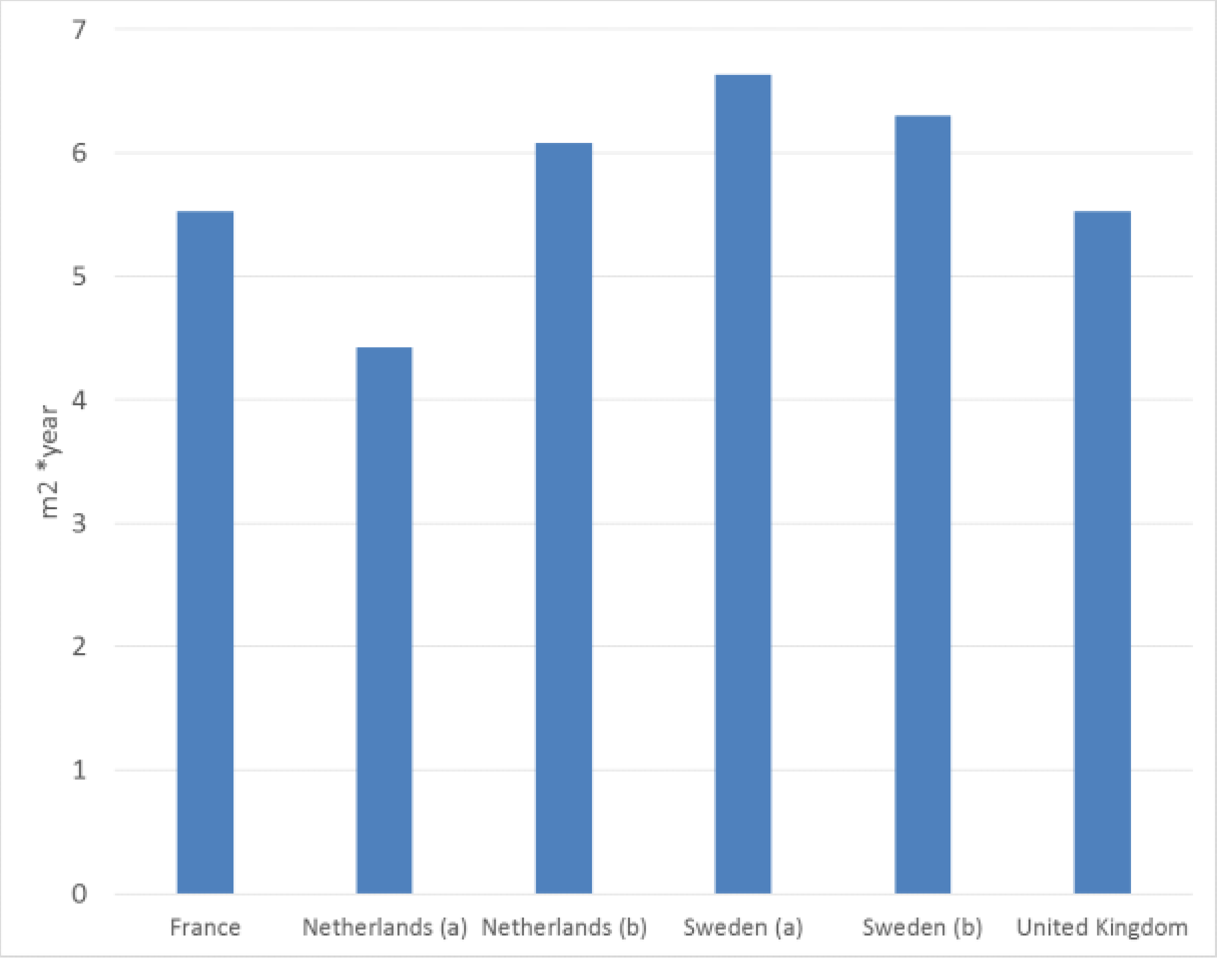

Figure 1.1: Land use per kilogram live weight at the farm gate meat from six international land use LCAs (France: Basset-Mens & vander Werf 2005; Netherlands (a): Blonk et al 2008; Netherlands (b): Zhu-XueQin & van Ierland 2004; Sweden (a): Cederberg & Flysjo 2004b; Sweden (b): Strid Eriksson et al 2005; United Kingdom: Williams et al 2006)

Each of these management differences can impact land use calculations and therefore direct comparison of the numerical results from different studies must account for these effects. The methodologies, inventories, and impacts associated with land use assessments are relevant to this study in that the critical role of ration production is highlighted.

1.2.3 Other Regions/Studies

Several LCAs conducted outside of the EU and US were also reviewed. Wiedemann et al. (2010) found significant differences in the sources of greenhouse gas emissions between EU and Australian pork production, but did not report land use. Dong and colleagues reported on GHG emissions in China, but did not include land use (Dong et al. 2007a, 2007b, 2005). Olea Perez et al., (2009) compared GHG emissions, acidification and eutrophication for standard, intensive production and low intensity or organic production in the UK and Mexico and reported that GWP for organic production in the UK was lower, but acidification and eutrophication were higher than standard production. However, the low intensity production in Mexico had lower impact in all three categories. Ogino et al. (2013) reported on Japanese production impacts to

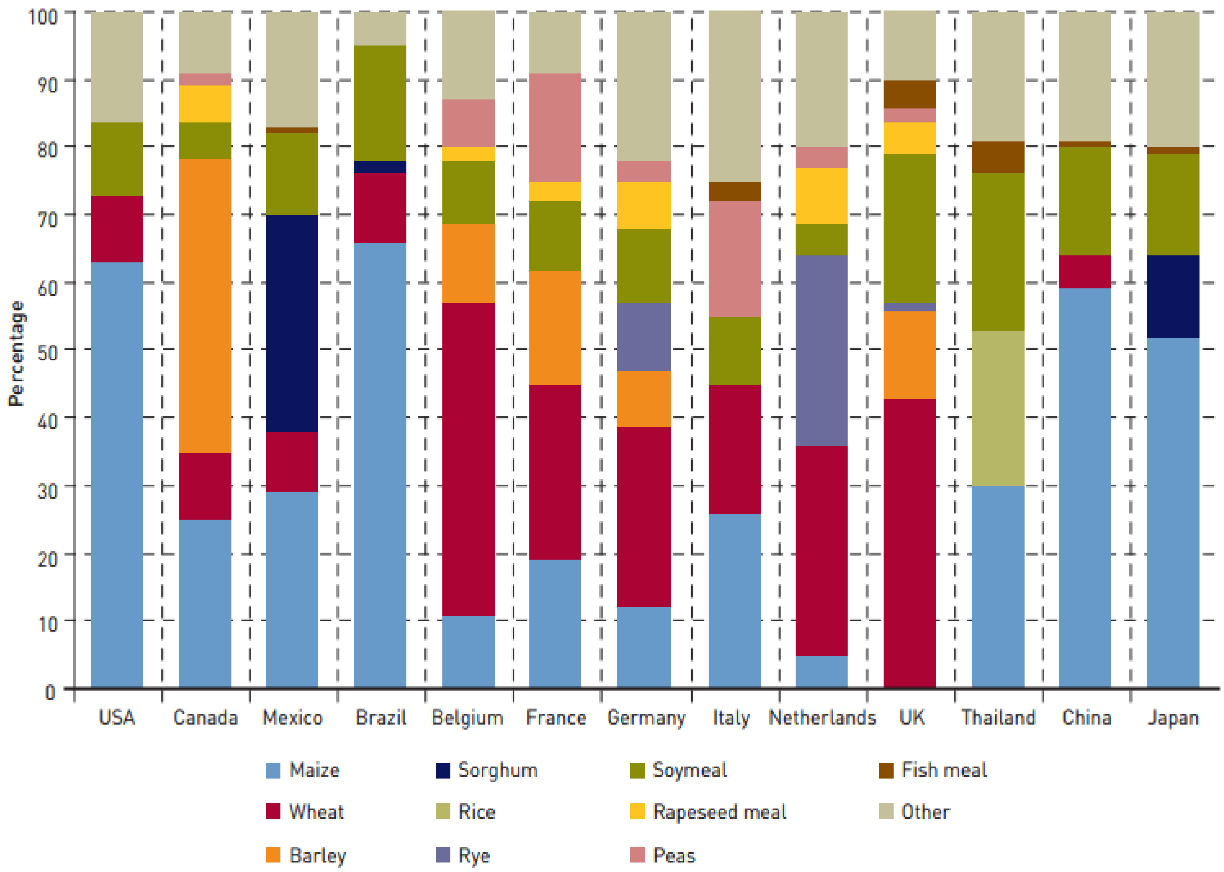

Figure 1.2: Average swine feed composition in various countries.

global warming, acidification and eutrophication, but again did not mention land use or provide sufficient background data to extract an estimate of LU.

In addition to pork LCAs, similar studies conducted by other agriculture and livestock organizations were reviewed to inform the methods and approach for a land use footprint for the US pork production industry. For example, Macleod et al. (2013) reported that 13% of GHG emissions from the global swine production supply chain arise from land use change (transformation) driven by increased feed demand; they did not consider land occupation effects. Another study (Cederberg et al. 2009) reported land use for beef production to be three to four times higher in Brazil than in Europe. In addition to reporting land requirements for production of animal LW at the farm gate, some researchers report land use efficiency as the production per hectare of land occupied (e.g., Basarab et al. 2012). Of all the assessments reviewed, only a handful quantified land use. Figure 1.3 displays some of the results.

An LCA conducted on margarine (Milà i Canals et al. 2012) included off farm land occupation in post-agricultural stages. Land requirements for feed mills and refineries were accounted including the “urban green areas” or areas around production facilities consisting of paths and vegetation. These land areas were allocated across the amount of product produced per year from that facility.

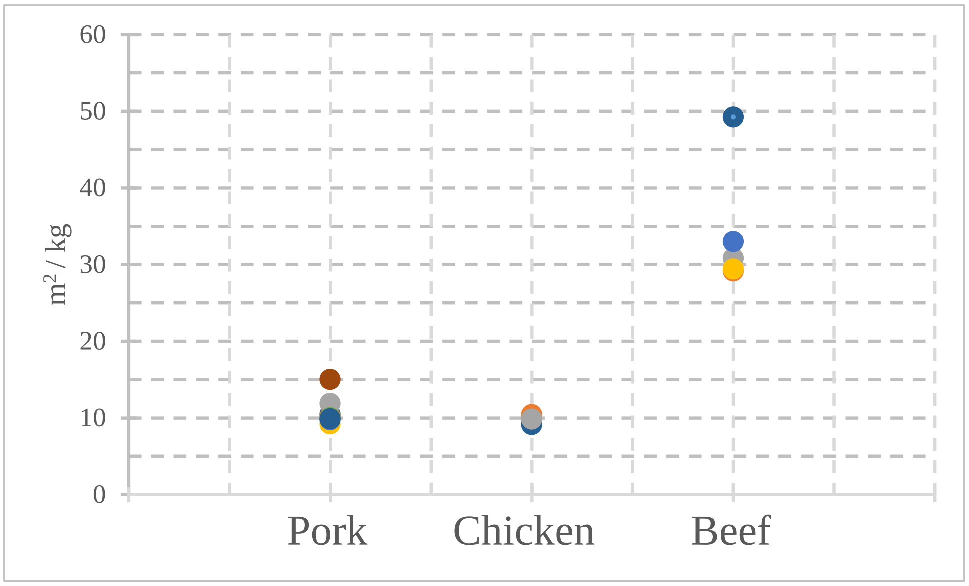

Figure 1.3: Land use footprint EU livestock products in kg of ***edible*** *meat (as compiled by* de Vries and de Boer 2010)

Meul et al. (2012) reported on the variation of the land occupation requirement for feed rations, all constructed to the same nutritional value, as a function of composition with a range from 1.04 to 1.53 m^2/kg feed emphasizing the potential of alternate ration formulations as an opportunity for influencing the land requirements (and impacts) of pork production. In an earlier, similar study, van der Werf et al. (2005) report a weighted average value for Bretagne, France of 1.7 m^2/kg feed. Another consideration is that synthetic ration additives like amino acids can reduce impacts associated with the production of feedstuffs (Cederberg and Flysjö 2004; Strid Eriksson et al. 2004; Ogino et al. 2013; Garcia-Launay et al. 2014). Mosnier et al. (2011) quantified the land area reduction for several amino acid substitution scenarios and reported potential cost savings of 28 Euro / ton and, reductions in land requirements ranging from 1.67 to 1.40 m^2/kg ration.

1.2.4 System boundaries

System boundaries, functional units and other methodological choices must be clearly defined and equivalent in order to compare results between LCAs. Three successively more inclusive boundaries are often used: field (inclusive of all upstream activities) to farm gate, field to fork, and cradle to grave (Figure 1.4). A majority of the LCAs reviewed applied the field to farm gate boundary. Eriksson et al. (2005) used the field to farm gate boundary as well, but chose an unusual functional unit: 1kg of pig growth (weight gain) from 29-115kg of weight. The results of this study did not report land use in terms of m^2 per kilogram edible meat. However, Nijdam et al. (2012) converted the findings into a land use footprint of 15 m^2/kg edible meat, but did not describe the methods used to obtain that result. Eriksson et al. focused on three protein source scenarios; one using locally grown peas, another similar feed supplemented with synthetic amino acids, and a third feed utilizing imported soy. It is likely that these feed choices could be the reason for such a large footprint when compared to the other assessments.

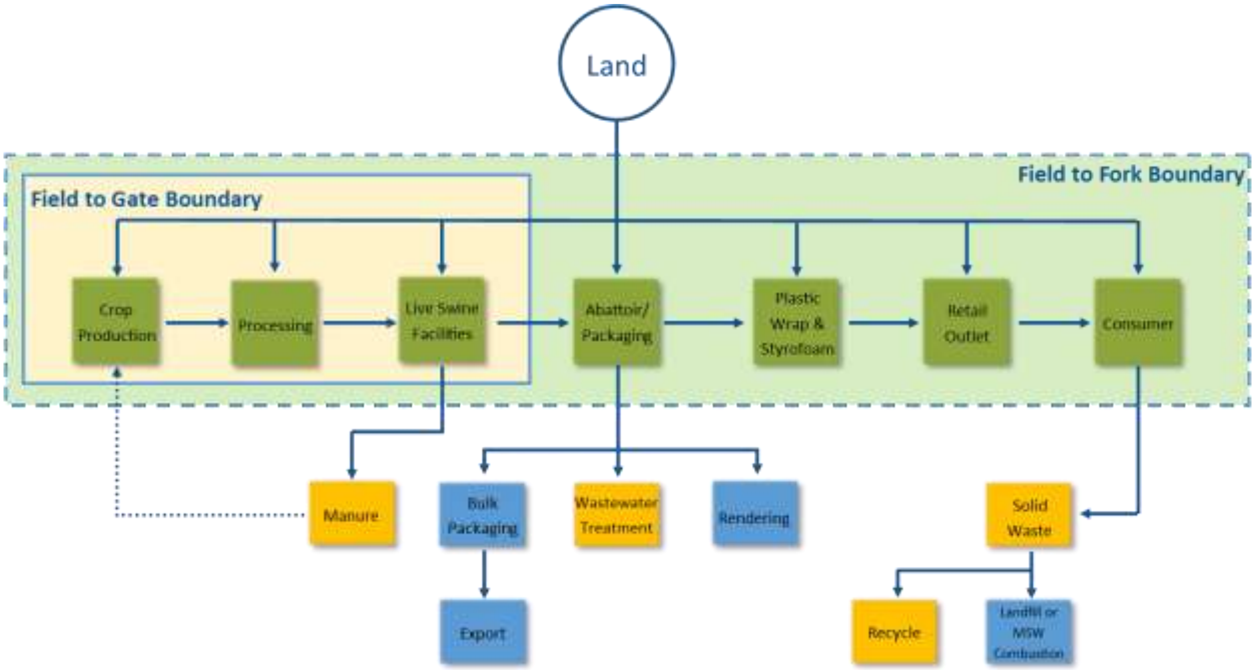

Figure 1.4: System boundaries for pork land use LCAs

Only two studies reported a full cradle-to-grave analysis of pork production (Zhu and van Ierland 2004) using a functional unit of 1000 kg of edible protein delivered. Based on the conversion factors provided in the paper, this is equivalent to 4.7 m^2/kg LW or approximately 8.8 m^2/kg edible meat. This footprint was roughly equivalent to the average of all the studies that did not include post-farm gate processes because land use was not accounted in the post-farm supply chain. Blonk et al. (2008) reported the cradle-to-grave footprint of pork production to be 8 m^2/kg (presumed edible, based on tabulated diets evaluated); this work also did not report post-farm gate land use inventory.

1.2.5 Co-product allocation

All of the reviewed studies applied economic allocation to account for multifunctional processes that produce by- or co-products. One study (Cederberg and Flysjö 2004a) used mass and energy allocation in addition to economic analysis in order to perform a sensitivity analysis. Because the majority of studies used the farm gate as the system boundary, the main allocation issues were from feed milling or other by-products such as distiller's grain. In the cradle-to-grave analysis, additional allocation at the meat processing facility was required. This LCA will follow the previous work and also adopt economic allocation beyond the farm gate.

1.2.6 Production methods

Several studies compared conventional to organic pork production and found significant increases in land use for organic production (Halberg et al. 2008; Williams et al. 2006; Basset-mens and van der Werf 2005). Halberg et al. (2008) reported values ranging from 6.9 to 9.2 m^2/kg LW for a variety of production systems with different level of outdoor rearing practices (all outdoor to partially outdoor). Increases in land use were found in a scenario modelled for “animal welfare” in a study by Cederberg and Flysjo (2004). However, there was some disagreement as to whether or not increases in the land footprint of organic systems resulted in larger impacts in other categories. Williams et al. (2006) found that the increased land footprint of organic systems resulted in lower carbon emissions in agreement with the study by Perez et al. (2009).

1.3 Land use inventory requirements for US swine production

This report provides context regarding land use for the live swine production phase of the United States (US) pork chain. Extant studies focused on field to farm gate processes revealed the most pertinent information regarding land use in pork production and the impacts associated with it. Information was also collected for the scan-level LCA, which encompassed processes from field (feed crops) to fork (consumption). Land use input requirements and system boundaries for both levels of analysis are presented in Figure 1.4.

1.3.1 Off-farm land use

Off-farm land use generally refers to the land required to produce the feed. The calculation of off-farm land use requirements are generally derived from crop yield data, feed conversion averages for swine, and the composition of feed rations. Feed composition data came directly from suppliers. All studies allocated land used by crops for one whole year. As previously mentioned, the two cradle-to-grave studies ignored post-farm land use in their inventory (Zhu and van Ierland 2004; Williams et al. 2006).

1.3.1.1 Crop production

Feed is the single largest contributor to land use in the pork production process (Basset-mens and van der Werf 2005; Williams et al. 2006). The possibilities for formulation of rations are nearly limitless and different combinations of ingredients may have significantly different land use requirements. Specific crop yields contribute more to uncertainties associated with land use than feed to pig weight gain ratio (Basset-mens and van der Werf 2005), suggesting that maximizing the use of crops with the highest yields could have the largest effect in reducing the land footprint. However, simply using the highest yielding crops is not entirely feasible as there are established nutrient requirements for swine production (National Research Council 2012). These dietary guidelines were established to reach certain performance standards such as daily weight gain and are largely corn and soymeal based to represent typical US feed ration composition. The same crop will have different yields depending on the area of the country in which it was grown, as well as from year to year due to weather variability (Figure 1.5). Iowa corn in 2012 illustrated this multi-year variability, when yield was well below the 10-year average. There are, of course, potential trade-offs between sustainability metrics: Using a locally sourced feed may have lower greenhouse gas emissions than a feed transported from a more distant yet higher yielding area of the country.

The advent of least cost formulation of swine feed has created constantly changing feed compositions that make it challenging to quantify feed impacts beyond common feed

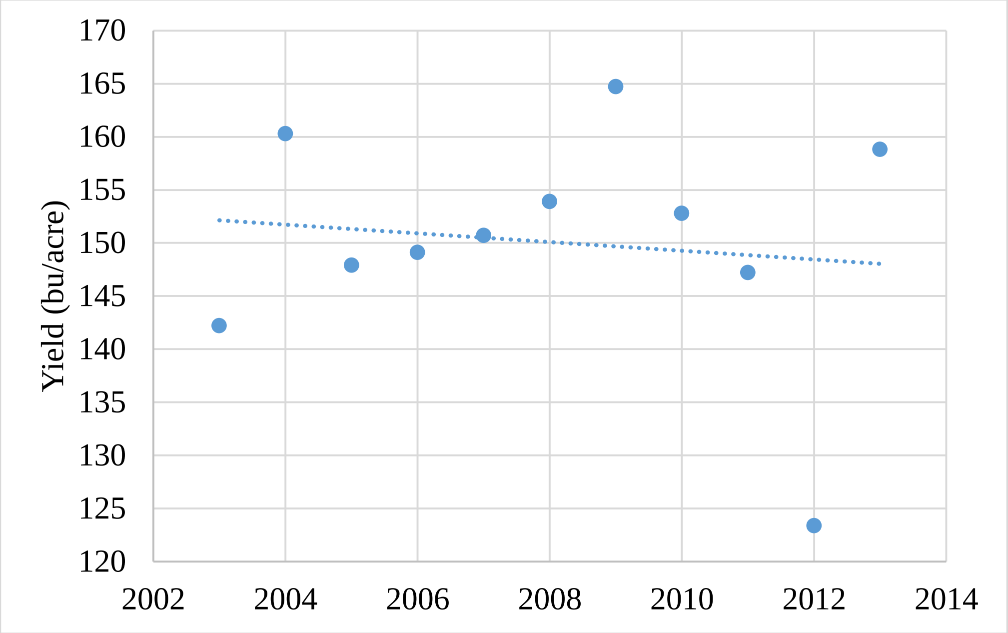

Figure 1.5: The inter-annual variability in yield is important to consider in LU analysis of swine production. The agricultural census data of 2012 have been recently released; however, use of those data alone would bias the study results.

configurations. Figure 1.6 and Figure 1.7 show the major feed ingredients for common diets of sow and pigs with and without the use of dried distiller grains (DDGS). The use of DDGS in swine feed has been occurring for over fifty years in part because of their favorable nutrient characteristics. During the first decade of this century, expansion of corn ethanol plants increased DDGS production and thus increased their use in feed (Stein and Shurson 2009). Use of DDGS in feed rations has been shown to increase the carbon footprint (Thoma et al. 2011a)

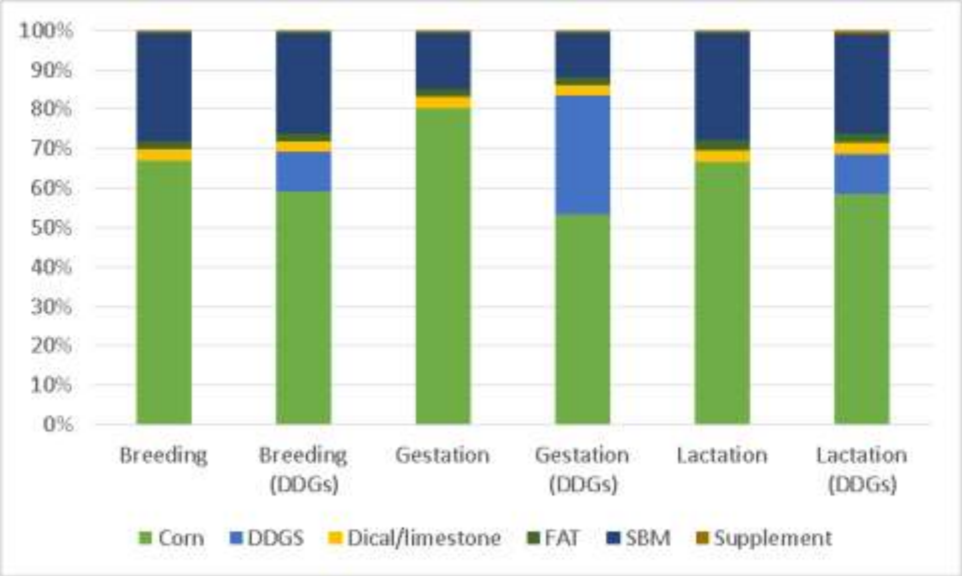

Figure 1.6: Sample sow feed rations (2012 NRC)

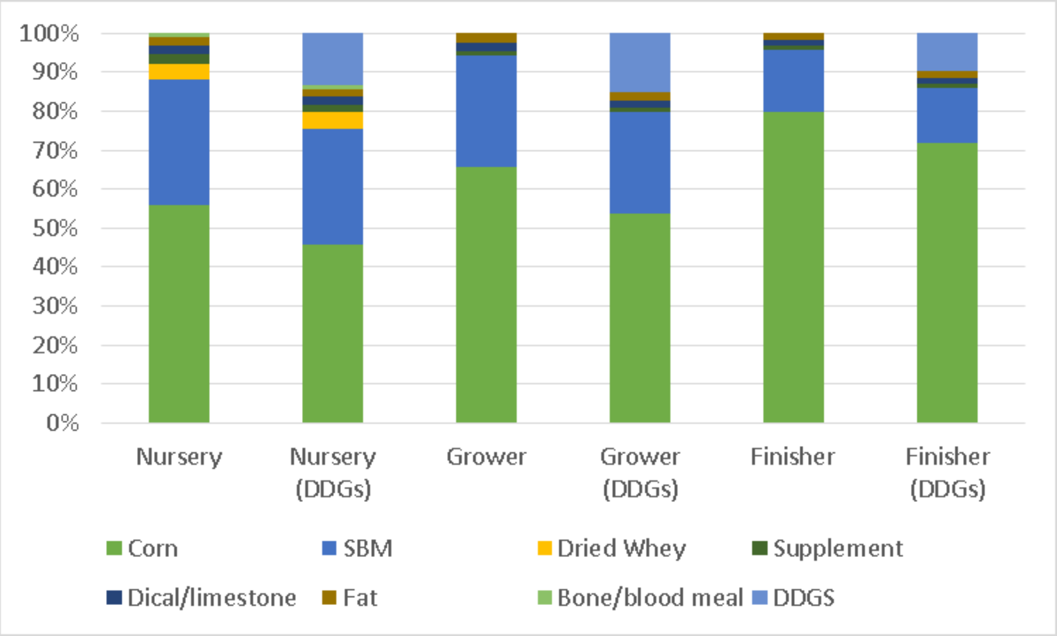

Figure 1.7: Sample pig feed rations (KSU 2007 Swine Nutrition Guide)

and is commonly added in swine rations therefore was considered in this study to evaluate potential effects on land use.

1.3.1.2 Feed processing

Very little information was found regarding land used in processing feed ingredients prior to delivery to the live production facility. However, grains are generally processed during the conversion to animal feed. These processes may include heating, rolling, crushing, milling, pelleting, or any other number of alterations. This step improves nutrient uptake in swine by increasing digestibility, or in the case of corn, achieves economic benefits (Richert and DeRouchey 2007). Milà i Canals et al. (2012) reported, for palm oil, land occupation values of 0.014 m^2 year per metric ton of processed fruit and 0.041 m^2 year per metric ton of oil. These numbers were based on a ratio of 3:1 for green space owned and occupied by the facility to the actual land occupied on site for factories. Those numbers were used to represent the land use footprint of all other oil crops in the study, and could be a viable surrogate to model land use by production facilities for swine feed rations.

In a 2006 survey, it was reported that 35% of hogs were fed grain produced by the swine operation, and that over half of all hogs produced in the US were given self-prepared feed (it is not reported what fraction is on-site vs. milled) (Lawrence and Grimes 2007). Unless yield differences can be documented, it is not likely that preparing feed on the farm or purchasing it from a supplier has any effect on land use. They report that 64% of US hogs are fed split-sex rations, which can impact feed conversion ratios.

1.3.2 On-farm land use

A majority of studies referenced national databases, site visits, and personal communications in order to inventory on-farm land use. In one study (Williams et al. 2006), the live pork production housing facilities and the areas devoted to roads and walkways at the production facility were included in the accounting. On the other hand, Basset-Mens and van der Werf (2005) only accounted for land use for crops and feed production. The level of detail in the inventory generally presented in the studies reviewed does not allow a detailed view of the contribution of LU from different production stages.

1.3.2.1 Live swine facility

Two types of production facilities were reviewed: conventional and hoop barn-based (Figure 1.8 and Figure 1.9). Alternatives to these scenarios generally involve outdoor production practices and were not focused on in depth because 94% of all hogs sold in the US were raised indoors (Lawrence and Grimes 2007). Conventional facilities are the most common and typically consist of rectangular buildings composed of concrete, wood, and steel. Conventional systems generally utilize tunnel ventilation or drop curtains. Hoop barns are structures that have an arch or teardrop shape and are typically constructed of lumber, steel arches, and a polyethylene tarp for the roof. Hoop barn systems require extra barns for bedding storage and an exterior manure storage pit, whereas conventional systems generally utilize subsurface manure pits and require less bedding. Surface area requirements for farrowing facilities for either approach are nearly identical. However, calculations of pig area for conventional grow-finish and gestation facilities in Table 1 include walkways and other areas present in the buildings but not used directly for swine production. Hoop barns are largely devoted to the pigs, but extra area is required for outdoor walkways between individual barns.

1.3.2.2 Production phases

Live swine production involves four distinct phases: gestation, farrowing, nursery, and grow-finish. It is common in the US for some of these individual phases to take place at different facilities. For example, 29% of all hogs sold annually in 2006 in the US came from facilities that were only wean to finish (Lawrence and Grimes 2007). Each phase of production has different requirements for space, depending on the type of production facility and the number of pigs produced. Table 1 provides an overview of the space requirements for each production phase

Figure 1.8: Conventional swine production facility (www.liquidfeeds.com, 2014)

Figure 1.9: Hoop barn system (www.leopold.iastate.edu/hoop-group, 2014)

based on a production capacity of 5,200 pigs per year using the most common production phase techniques.

Farrowing

During the farrowing phase, sows are housed in individual farrowing crates. These crates are generally 1.9 m long and 0.6 m wide. One farrowing barn may have as many as 10 rooms with 14 crates per room. Over 90% of pigs produced in the US come from farrowing crates (Purdue Extension. 2008). Recent criticism of the farrowing system has spurred an interest in suitable alternatives. Table 2 summarizes the required space for alternative systems.

Table 1.1: Surface area requirements for live swine production facility (5,200 pigs/year)[a]

Production Phase	Building Area (m^2)	Pig Area (m^2/pig)	Description
Farrowing	293	6.1	4 rooms of 12 crates
Nursery	473	0.5	4 rooms of 22 pens
Grow-Finish			
Conventional	1426	0.9	4 rooms of 8 pens
Hoop	1594	1	8 hoop barns
Gestation			
Conventional	702	2.3	Individual gestation stalls
Hoop	1794	5.2	9 hoops barns

[a] Lammers et al. (2009)

Table 1.2: Comparison of size requirements for farrowing systems[a]

Farrowing System	Size (ft.)	Increase over crate
Turn-around	5 x 8.5	21%
Sloped Pen	7 x 7	40%
Family Pen	5.5 x 7.5 + 1.3 x 3.25	30%
Werribee Pen	7.6 x 11.4	147%
Ellipsoid Crate	5.6 x 6.5	21%
Outdoor English-style Hut	9 x 5.4	9%

[a] Purdue Extension 2008

Gestation

There are a variety of housing options for gestation depending on the requirements of the producer. Feeding, watering, and environmental needs must be taken into consideration along with space requirements. Common US swine industry practice is to house gilts and sows in individual stalls. This method allows inspection of the pigs in order to ensure proper feed intake and reduce physical aggression among females. Some producers choose to house gestating sows in groups. This practice can be more difficult, especially for larger operations; however, there is an increasing demand for this type of gestation housing. Gestation facilities that utilize stalls are most efficient and allow 16 ft^2 (1.5 m^2) per gilt and 20 ft^2 (1.9 m^2) per sow. Converting the same facility to group housing decreases the amount of swine that can be housed by 5-20% (Purdue Extension. 2008). The use of hoop barns for gestation requires a minimum of 24 ft^2 (2.25 m^2) of bedded area per sow. Figure 1.10 shows the average surface area needed per pig by phases of production. All values are for group housing, except sows, which are housed individually.

Nursery

Pigs can be housed in groups or individually during the nursery production phase. During this phase, pigs are young and experience the most rapid growth. If space is too limited, then pigs will experience a decrease in their rate of weight gain. Therefore, if pigs are housed in groups it is advantageous to allocate them based on size and weight to ensure optimal free space. However, in some situations, free space can be reduced by up to 50% without a decline in growth rate (McGlone and Newby, 1994). Feeders that supply water (wet/dry feeders) can increase the amount of pigs per feeder space. Grouping pigs provides the most efficient use of space with as little as 1.75 – 4 ft^2 (0.16-0.37 m^2) required per pig. Individual housing results in a required space of 5.8 ft^2 (0.54 m^2) per pig (Mcglone et al. 2010)

Grow-finish

The grow-finish phase is the final stage in live swine production. Swine are raised to market weight in groups or individually. Average market weight in the US is 275 lb (125kg). As the pigs approach the desired weight, they require more space per pig. For this reason, some producers choose a continuous flow system, but all-in all-out is preferred (Mcglone et al. 2010). Individual pig housing is much less economical as it requires more space per pig and older pigs

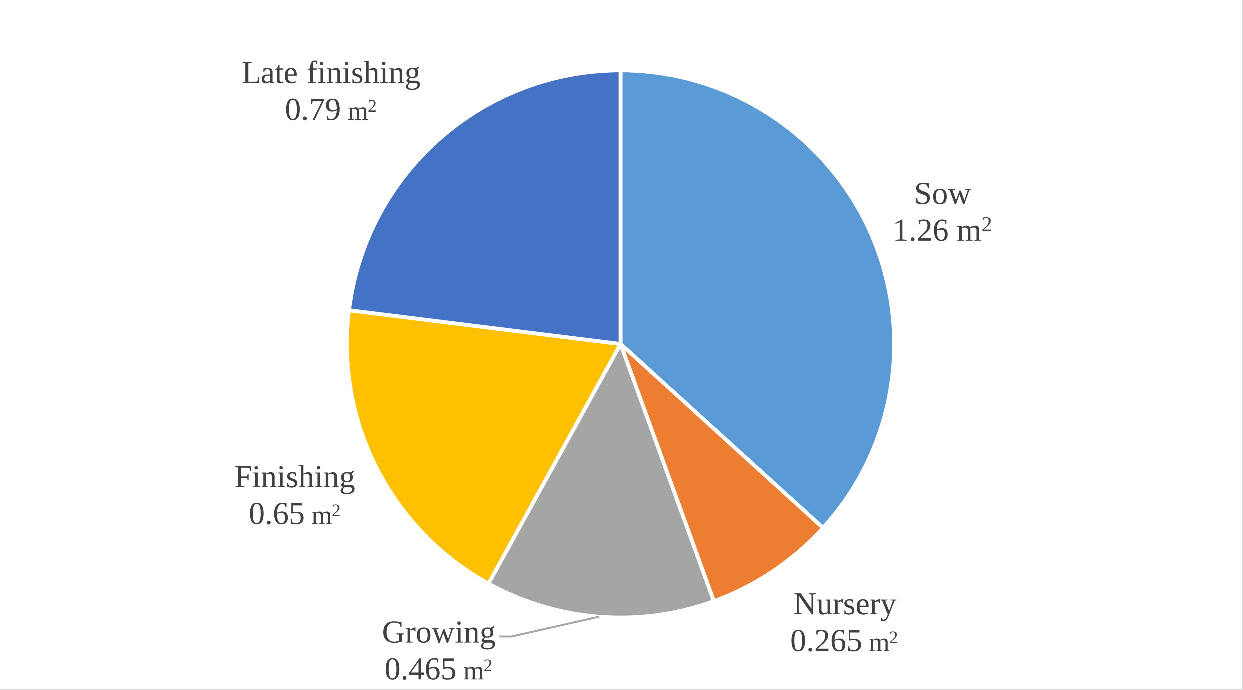

Figure 1.10: Average surface area needed per pig for each phase of production (Mcglone et al. 2010)

are tolerant of a wider range of environmental conditions than younger ones. The space needed per pig in grouped housing ranges from 6 – 9 ft^2 (0.56-0.84 m^2) depending on body weight. Groups greater than 20 pigs per pen could use even less space per pig. Gonyou et al. (2006) presented an equation for calculating the floor space needed for grow-finish pigs based on body weight (BW) and space coefficient (k). A k value of 0.336 was developed for grow-finish pigs housed in barns with fully slatted floors.

$$A = K \times BW^{0.667}$$

1.3.2.3 Production sites

The land these facilities occupy also include access roads, a buffer area between buildings, and other green space. Lammers et al. (2009) found that if all phases were located at one site with a production capacity of 5,200 pigs per year, then a conventional facility and a hoop barn-based facility would require a total land area of 11,868 m^2 and 16,671 m^2, respectively. Dividing the total land area by the production capacity results in an annual live production facility land footprint of 2.28 m^2 per pig for conventional systems and 3.21 m^2 per pig for hoop barn systems. Hoop barn systems in this scenario resulted in a 40% increase in the on-farm land footprint. Lammers et al. (2010) also developed a scenario for conventional and hoop barn systems with annual capacities of 15,600 pigs per year.

It was found that a conventional system of this size resulted in an annual live production facility land footprint of 1.59 m^2 per pig and 2.06 m^2 per pig for the hoop barn system; this is largely the result of better utilization of the 'fixed' land use associated with buffer regions and green space. Larger operations may also realize gains in efficiency elsewhere that could result in a lower land use footprint. For example, Figure 1.11 shows that larger production facilities produce more pigs per litter than their smaller counterparts, which decreases the relative land use requirement. The trend of US hog production toward fewer facilities with larger inventory (Figure 1.12) could result in a smaller and smaller live production facility land use footprint for US swine

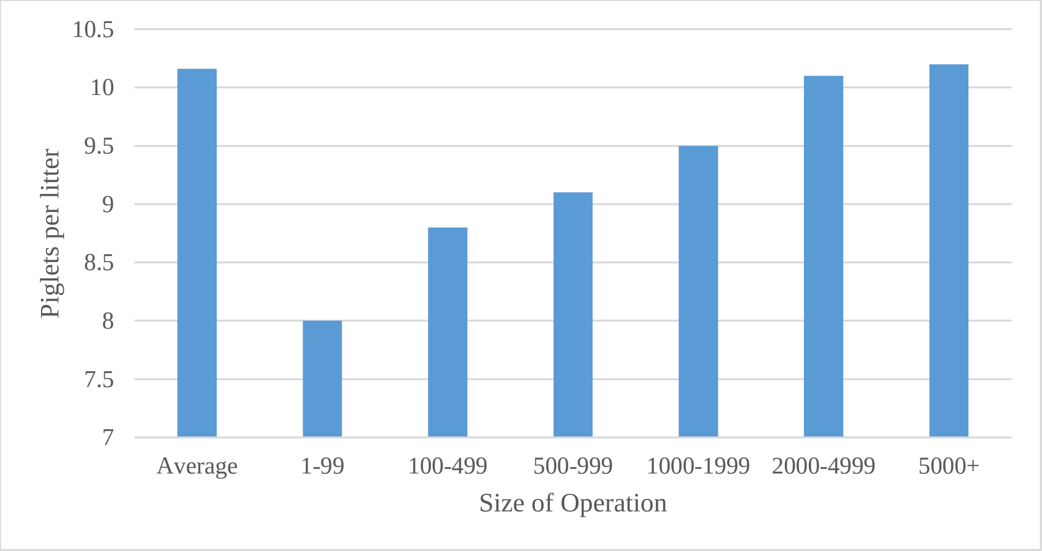

Figure 1.11: US pigs per litter by size of operation (NASS 2013)

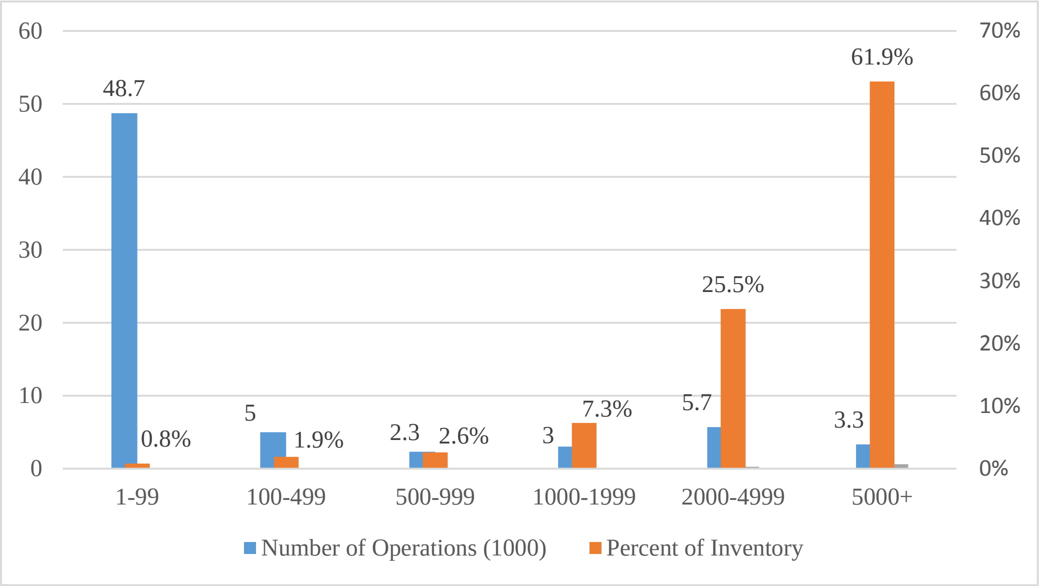

Figure 1.12: Number of US hog operations and percent of national inventory for 2012 (NASS 2013)

production. However, these improvements are likely to be very small with regard to the overall land requirements, which, as previously stated, are largely determined by feed production requirements.

1.4 Land use impact assessment

Here we present a brief introduction to impact assessment, and will include a full review and summary of the United Nations Environment Programme and Society of Environmental Toxicology and Chemistry (UNEP-SETAC) international effort in conjunction with the detailed LCA of live swine production. Land occupation and transformation, largely driven by humanity's need for food, feed, fuel and fiber is acknowledged to affect biodiversity and the ability of the land to provide ecosystem services such as biomass production and water purification, among many others (Milenium Ecosystem Assessment 2005; Milà i Canals et al. 2007). Biomass production is the largest human land use and has significantly benefited mankind. Since biomass production is also associated with growing costs in terms of degradation of other ecosystem services (Millenium Ecosystem Assessment 2005), it is now critical that impacts be assessed in order to help guide land management to maintain healthy and productive soils. Deterioration of ecosystem services directly affects the US pork industry, as feedstuffs for swine account for the majority of supply chain land use. Assessing land use impacts helps to identify potential environmental hotspots and allows stakeholders to make informed decisions that minimize impacts on biodiversity and ecosystem services, thus ensuring the continued ability of land to supply life support functions.

Figure 1.13 is a simplified representation of how transformation and occupation processes can impact land quality over time. Here land quality represents the overall ecosystem services provided by the land, not strictly the agronomic quality. The principle underlying this diagram is that while there are obvious effects of transformation (e.g., loss of rainforest), there are also effects to ecosystem quality associated with continued occupation and management of the land. There is, necessarily, a judgment required regarding the original state against which the transformation and occupation of the land is assessed. Koellner and Geyer (2013), among others, refer to this original state as the "reference situation" and there are many viewpoints among LCA researchers as to which is the most appropriate. The potential natural vegetation for an area is a viable point of comparison, as is the land use mix from a certain time period in the recent past. This, among other issues, is part of the ongoing international discussion in the LCA community regarding incorporation of land use into LCA.

Until recently, international discussion has focused on land occupation inventory. Land use (as inventory) in LCAs has often been described as an impact indicator – based on the assertion that land occupation by human activity has an unspecified impact on biodiversity and other ecosystem services. It is also a convenient way to denote the use of a scarce resource. Here we present a brief introduction to the current work stemming from the first phase of the UNEP-SETAC Life Cycle Initiative (Milà i Canals et al. 2007) which is moving the field of LCA towards impact methods which treat land use, as discussed above, as an inventory flow. Treating land use this way allows for the impacts of transformation and occupation on the environment to be assessed using lifecycle impact assessment methodology in a manner that is similar to the way climate change is assessed: the inventory is multiplied by a characterization factor to denote a midpoint impact, like global warming potential which places all greenhouse gases on an equivalent scale of CO_2 equivalents. Of course, the physical basis for evaluating global warming potential is relatively simple compared to the task of quantifying land use impacts to ecosystem services because of the spatial and temporal resolution needed and often non-linear responses to disturbances observed in ecosystems.

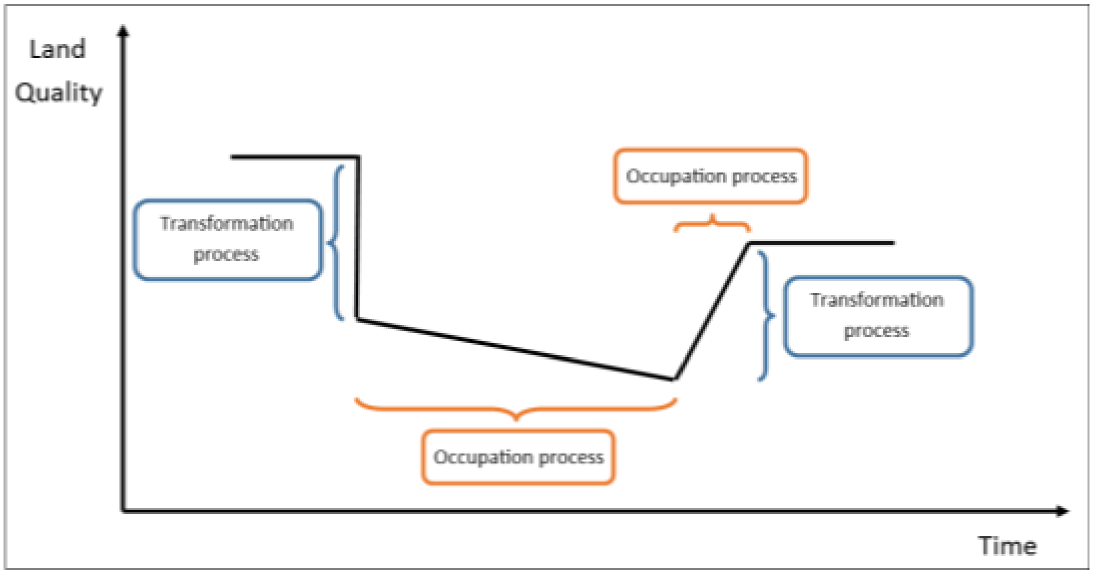

Figure 1.13: A simple representation of how land quality can change with use (adapted from (Lindeijer 2000)*)*

Despite the challenges, new land use impact assessment methodologies are being put forward in an effort to achieve a life cycle impact assessment method that is globally applicable, regionally-specific, and capable of utilizing a set of characterization factors that link land use flows (land occupation and transformation) to impacts on the environment (de Baan et al. 2013; Souza et al. 2013; Müller-Wenk and Brandão 2010; Beck et al. 2011; Brandão and I Canals 2013; Saad et al. 2013; Milà i Canals et al. 2012; Koellner et al. 2013). These impacts can be represented by the endpoints ecosystem services and biodiversity.

One of the impact assessment methods we plan to use for the detailed analysis is the Integrated Valuation of Environmental Services and Tradeoffs (InVEST[2]) software model which is one of the tools being used to quantify land use impacts (Nelson et al. 2009; Tallis and Polasky 2009). InVEST creates maps that provide preliminary trends in biodiversity and ecosystem services that are valuable for showing the tradeoffs associated with different land use scenarios.

The final phase of this project is focused on taking the land use inventory from the scan and detailed LCA for swine production and using it in the emerging impact assessment methodologies. One methodology that is being explored during this phase is IMPACT World+. This is one of the most recent LCIA methodologies that has been developed by a group of LCIA expert researchers[3]. This method includes regionalized characterization factors for the impacts of land use at spatial scales and associated variability previously unavailable in LCA modeling. A more detailed review of the literature, current methodologies, and work of the UNEP-SETAC working group will accompany that report.

1.4.1 Current gaps in knowledge

The single largest impediment to an accurate land use inventory in LCA is the absence of knowledge of geographic provenance of commodity products used in swine feed. The significant variability in yield and land transformation coupled with the poor traceability of feeds increases uncertainties in assessing the land use impacts of swine production.

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[2] http://www.naturalcapitalproject.org/InVEST.html#Tech

[3] http://www.impactworldplus.org/en/publications.php

2 Scan-Level Life Cycle Assessment

2.1 Introduction

Global growth and development place high demand on arable land in an attempt to feed an expanding population that now totals over 7 billion people. The impact of these forces on the capacity of land to provide ecosystem services and support natural assets, like biodiversity, are not well understood. Quantifying the human influence on terrestrial resources is critical to guarantee the longevity of our food systems.

Pork is the most widely consumed meat in the world, representing some 37% of global meat consumption (FAO 2013). The US is one of the world's leading pork producers, second only to China. In 2012, the US swine industry accumulated sales of $22.5 billion, representing 6% of all agriculture sales in the US The farms producing a majority of these pigs are primarily located in the Midwest, with 5 of the top 10 producing counties in Iowa. Other Midwestern states such as Minnesota and Nebraska also have large pig sales. Production is centered in this region largely because it is the source of the majority of corn production, the primary ingredient in swine feed. With the average market hog consuming nearly ten bushels of corn in its lifetime, and annual US sales totaling nearly 200 million head (NASS 2012), the land use associated with corn grown for pigs is significant.

The National Pork Board (NPB) commissioned the Center for Agricultural and Rural Sustainability (CARS) at the University of Arkansas to perform a life cycle assessment (LCA) of United States pork production in order to quantify land use throughout the supply chain as a 4 phase project:

Task 1: Complete a literature review of land use impacts from animal agricultural production.

Task 2: Conduct a pork supply chain scan-level life cycle analysis of land use.

Task 3: Conduct a life cycle analysis of live swine production for land use.

Task 4: Complete final written reports.

First, a literature review was conducted in order to provide the most current information from other agriculture and livestock-related research. The results of this review were provided in a separate report. This report presents the findings of Task 2: This scan-level assessment accounts for all relevant land occupied from "cradle to grave" in the production of pork in the US The phrase "cradle to grave" refers to all processes required to produce edible pig meat. These range from inputs to the production of swine feed (i.e. fertilizer for crops) to processes required for consumption at the home. The LCA methodology was chosen for its ability to quantitatively analyze potential impacts and risks associated with complex systems. The resulting analyses are intended to inform pork producers, as well as educate the general public.

2.2 Methodology

There are four main phases involved in conducting a LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation. The interpretation step is conducted throughout, creating the iterative nature of LCA. This framework enables researchers go back and revisit each step of the LCA as they learn more about the problem at hand. The following sections outline the necessary components of LCA as they pertain to this study.

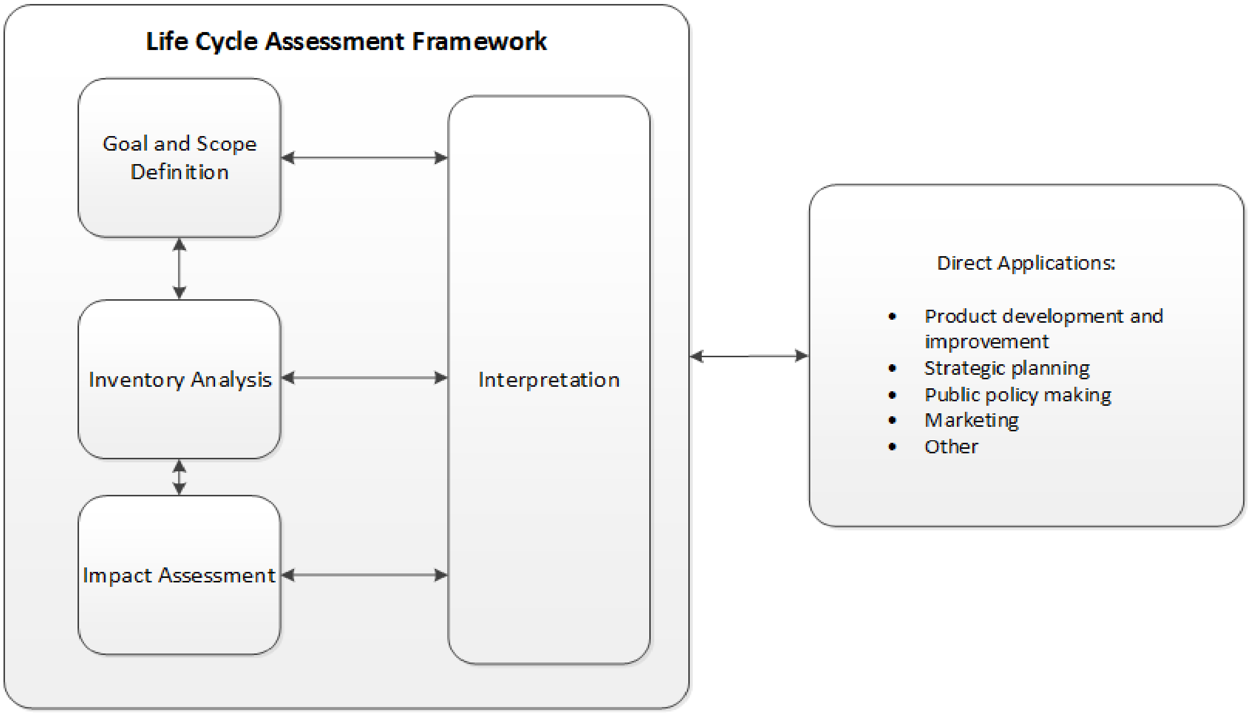

Figure 2.1: The four phases of Life Cycle Assessment (ISO14040:2006)

2.2.1 Goal and Purpose

The goal and purpose of a LCA create a roadmap for analysis. They help guide research efforts by defining the desired results in a way that has relevance and is useful to the intended audience.

The goal of this study was to quantify land occupation resulting from pork produced and consumed in the US at a national scale. These analyses built on information from previously conducted LCAs for the National Pork Board (Thoma et al. 2011; Matlock et al. 2014; Thoma et al. 2013), the Pig Production Environmental Calculator, peer-reviewed scientific data, and communication with industry experts.

The purpose was to investigate hotspots in the supply chain where land use was least efficient and to produce information useful for internal decision-making. Similar assessments have been conducted for international systems (Zhu and van Ierland 2004; Dalgaard 2007; Dalgaard et al. 2007; Fry and Kingston 2009; Wiedemann et al. 2010; Nguyen et al. 2012) and region-specific US systems (Pelletier et al. 2010; Stone et al. 2012). However, no study has been conducted that addressed land use in pork production on a national level for the US.

2.2.2 Functional Unit

For this assessment, the functional unit chosen was four ounces of boneless pork prepared for consumption. It was chosen to provide consistency among LCAs previously conducted for the NPB by CARS.

2.2.3 Scope

The scope of a LCA determines the system boundaries. These boundaries limit what processes will or will not be included in the analysis. For this scan-level assessment, the supply chain was divided into six stages: production of swine rations, animal rearing on the swine farm (with 3 sub-stages for sow, nursery and finishing barns), processing, packaging, retail, and consumption. Land used for transportation between each phase of production was not included because transport of resources for swine production was determined to be insignificant compared to the broad range of uses for public roadways. Land use associated with material contributions to infrastructure, such as wood used in the construction of barns, was included in the analysis. For capital goods, impacts were amortized over the expected useful life of the facility. Figure 2.2 displays the system boundaries of this assessment (defined as “cradle to grave”), as well as the boundaries for Task 3 (“cradle to gate”).

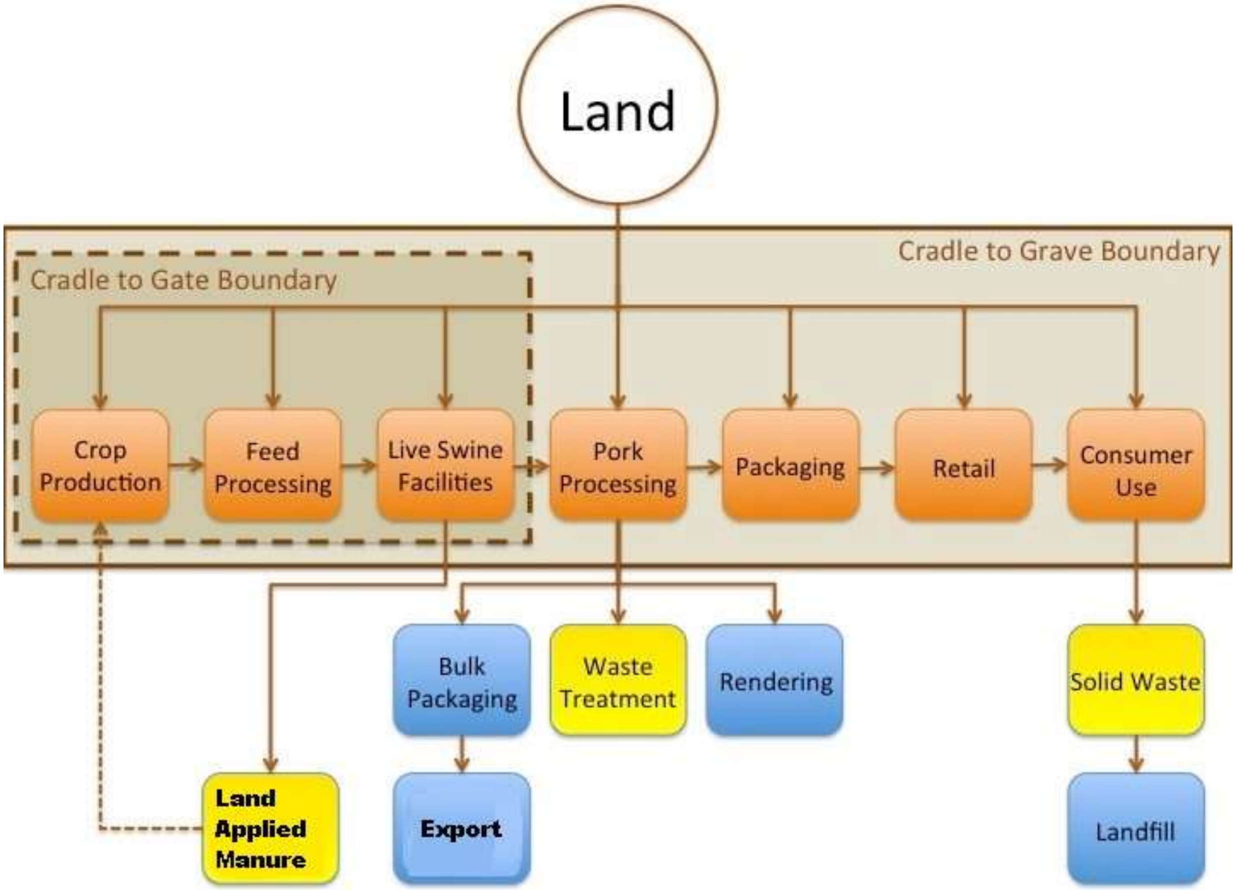

Figure 2.2: System Boundaries

2.2.4 Land Use

For the purposes of LCA, land use generally refers to two types of processes: land occupation and land transformation. This scan-level assessment only considered land occupation. Therefore, the terms “land use,” “land occupation,” and “land footprint” are used somewhat interchangeably. Results are presented in units of area occupied multiplied by time. In LCA, this is commonly reported as m^2a (square meters annum). Because of a lack of available information, we have assumed that the main crop is assigned the occupation for an entire year, including any fallow or inter cropping periods. For further information on land use processes, refer to the literature review from Task 1. Impacts associated with both land use processes (occupation and transformation) will be considered in Task 3 of this project.

2.2.5 Scenario Development

The pork production scenario for this LCA was adapted, in part, from prior LCAs conducted for the NPB. Swine farming was separated into three phases. Each phase was modeled in separate barns denoted: sow barn, grow barn, and nursery barn. All barns were modeled as the tunnel-ventilated type with deep pit manure storage facilities. Each phase of production was modeled as occurring on the same farm. In reality, this is often not the case as it is common in the US for pigs at different stages of development to be raised on different farms, sometimes widely separated. Modeling the wide variety of potential production scenarios is beyond the scope of this scan level assessment.

In order to account for differences in climate, production was modeled in each of the ten swine production regions (Figure 2.3) as defined by the United States Department of Agriculture (USDA). A location was chosen in each region that had representative climactic conditions (Table 2.1).

Table 2.1: Representative counties modeled and total production for each region

Region	Total Production (1000)	Representative State	Representative County
1	68	MA	Hampshire
2	350	NY	Cayuga
3	5,434	PA	Perry
4	38,840	NC	Wake
5	57,053	IN	Jasper
6	10,801	OK	Texas
7	74,719	IA	Hardin
8	11,128	SD	Edmunds
9	526	CA	Stanislaus
10	197	OR	Clackamas

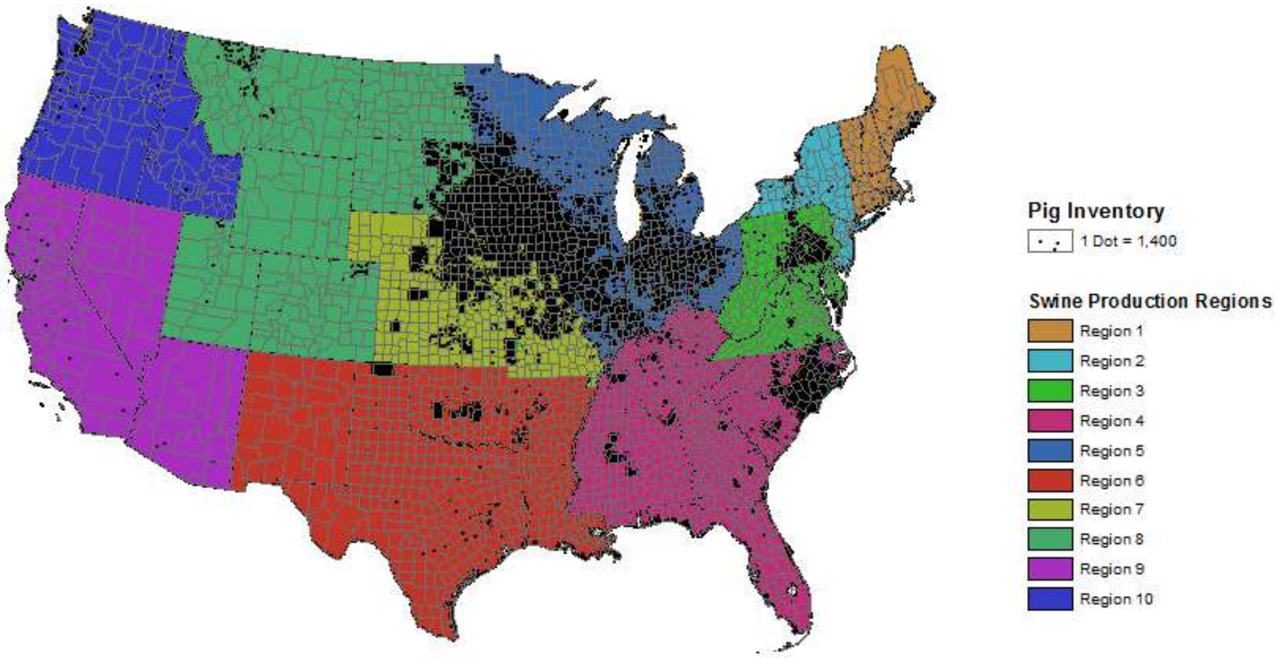

Figure 2.3: Swine production facilities in the US (2012 NASS)

2.2.6 Model Development

The modeling followed a two-stage approach. In the first stage, swine production parameters were used with the Pig Production Environmental Calculator (PPEC) to calculate lifecycle inventory for the system. The PPEC is a predictive swine farm model developed at the University of Arkansas that requires basic user inputs, such as barn dimensions and herd size, to estimate the productivity of a farm and its environmental resource requirements. The calculator accounts for production variables such as climate, management strategy, and feed composition. Output data from the PPEC were then used as inventory data for SimaPro V8, a modeling program commonly used by LCA researchers.

SimaPro enables users to analyze the potential environmental impact of production systems, in part, by utilizing a life cycle inventory database known as Ecoinvent. Ecoinvent serves as a library, providing data for “background” unit processes. For example, land use associated with the extraction of raw materials required to produce nitrogen fertilizer for corn production is considered a background process because it is not under the direct control of farmers. The amount of land use attributed to the functional unit from this process is likely to be very small, but the accumulated impact of background unit processes can be significant. Use of databases like Ecoinvent allows life cycle modelers to focus research efforts on major foreground processes, like those diagrammed in Figure 2.2, while maintaining a thorough inventory of impacts throughout the supply chain. The second stage of modeling used SimaPro to calculate land occupation in the production and consumption of 4oz of lean pork in the US

2.2.7 Life Cycle Inventory

The inventory analysis phase in LCA is the collection of all relevant inputs and outputs associated with producing the functional unit. During this phase, two land occupation classifications were inventoried and assigned to six supply chain stages as described above in §2.3.

2.2.7.1 Land Classification

Land occupation was categorized into two classes: agricultural and urban. Urban land use across entire supply chain accounted for less than 1% of the total footprint. Therefore, contributions from occupation classification were aggregated and then reported as one. The largest contributors to urban land use included occupation related to processing plants, retail locations, and various background unit processes from SimaPro (i.e. production of electricity). We did not include land occupation of the transportation infrastructure (roads) nor did we include land occupied by consumer's homes.

2.2.7.2 Allocation

In the case that an input was a by- or co-product of another process, an allocation of the environmental burden was established. The International Standards Organization recommends using a system expansion approach for allocation whenever possible. This approach requires detailed assessment of markets to identify substituted products and was considered to be beyond the scope of this project. This assessment allocated product burdens according to their economic value. All allocation values used in this assessment are from the work of Thoma et al. (2011).

2.2.7.3 Swine Rations

Corn and soy are the largest contributors to feed for swine in the US These two commodities make up the bulk of swine rations through corn grain, dried distiller grains with solubles (DDGS), and soybean meal (SBM). In order to inventory the land occupied by these crops, a five-year average (2004-2008) of crop yield was calculated using data from the United States Department of Agriculture (USDA) and the National Agricultural Statics Service (NASS). This time period was chosen in part, because previously conducted LCAs for the NPB used the same dataset, which provides consistency across assessments. All crops were assumed to occupy the land for one year and thus no accounting for double cropping is included.

The most recent NASS census data (2012) was considered for this analysis, but was ultimately not included because yields were significantly below average due to a severe drought. Interestingly, this data was shown to contribute significant bias to the average yield calculations. Figure 2.4 shows average corn yields for years 2002 to 2012. An obvious increasing yield trend is seen from the 10 year data range from 2002 to 2011 (green trend line). However, shifting the regression trend line by one year (2003-2012) to include yields of 2012, a year of devastating drought, significance is such that average yield is shown to trend in a negative direction (blue trend line). This highlights the need for critical assessment of data quality in evaluation of LCA.

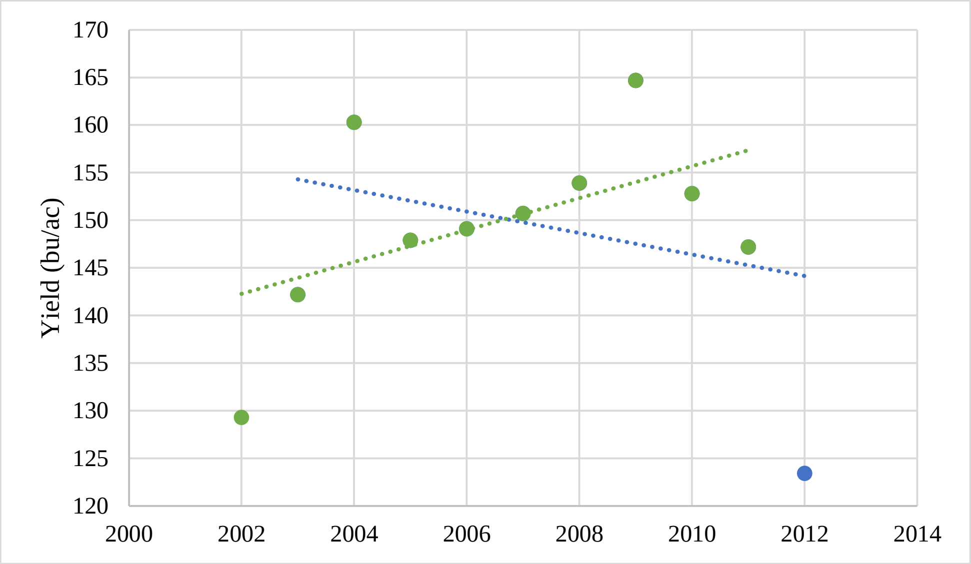

Figure 2.4: Average US corn yields for 2002-2012

A changing climate has the potential to increase the likelihood of events such as the drought seen in 2012. Lower yields can lead to higher prices for feed, which represents roughly two-thirds of the cost to produce pigs[4]. Therefore, one scenario was run using only 2012 NASS census data for comparison to demonstrate the potential influence of climate change on environmental performance of the sector.

Swine ration compositions are shown in Figure 2.5 for each barn modeled. Corn and soy comprise 88-98% of feed.

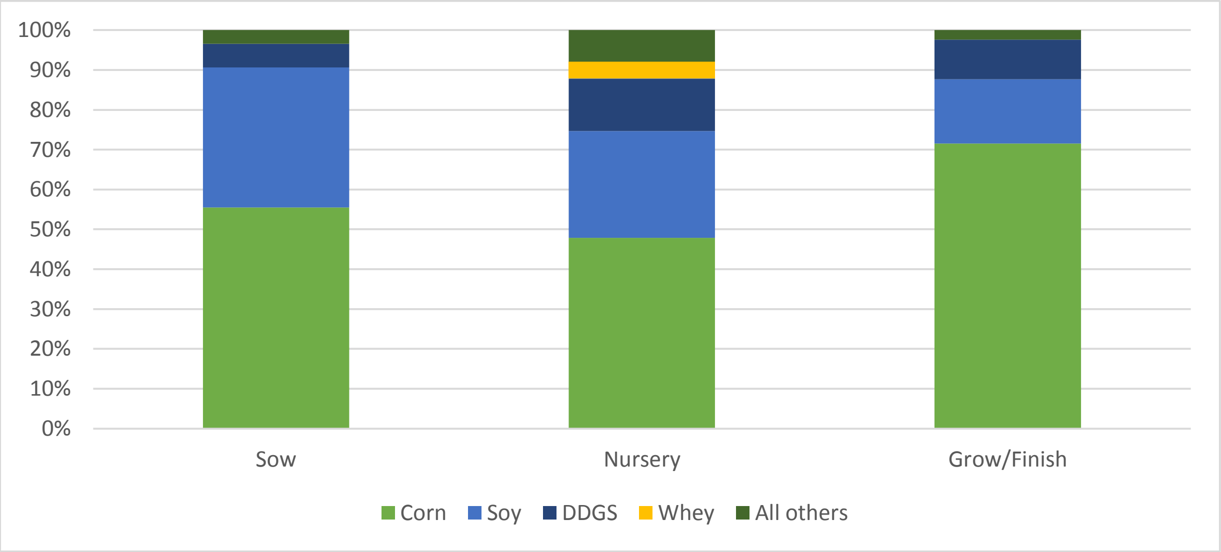

Figure 2.5: Largest constituents of swine rations by barn type

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[4] https://d3fns0a45gcg1a.cloudfront.net/sites/all/files/documents/Pork_Quickfacts_Stats_2014.pdf page 24

2.2.7.4 Byproducts

The use of DDGS in swine feed has increased recently due to economic considerations. DDGS are produced as a byproduct of corn-ethanol production and provide a low-cost supplemental protein. An allocation of 19.7% of the land occupation of corn production was attributed to their use in rations with the remaining burden attributed to ethanol production.

Soybean meal is another major constituent of swine feed. It serves as the primary source of protein and is produced along with soy oil during the processing of soybeans. An allocation of 56.5% of the land occupation was calculated for soybean meal and 43.5% allocated to soy oil. Land area for the oil mills was estimated from Milà i Canals et al. 2012 who calculated occupation for palm oil processing facilities.

2.2.7.5 Swine Farm

The following regression equation relating land use on farm to annual production capacity was calculated using data from two conventional swine facilities modeled by Lammers et al. (2009).

$$LU = 1.2502P + 5367$$

Where LU is land use on farm in square meters and P is number of pigs produced annually. Further information on the facilities modeled can be found in the literature review from Task 1.

Building materials required for construction of each barn were adopted from the work of Thoma et al. (2011). Barns were assumed to have a lifespan of ten years and land use associated with their material inputs were amortized over this period of time.

Input and output flows for pigs in each barn were adopted from previous LCAs conducted for the NPB to ensure consistency across impact categories. However, minor changes were made to some of the breeding parameters in order to represent the most current industry averages. Examples of the inputs used for modeled swine barns in this assessment are listed in Tables 2-4.

Table 2.2: A sample set of nursery barn model parameters

	Input/output	Units	Description
Initial weight	12	lbs	Weight entering barn
End weight	50	lbs	Weight leaving barn
Pigs in per cycle	500	pig/cycle	Maximum 5,000
Pig death per cycle	15	pig/cycle	Pig deaths per barn cycle
Time to cleanout	5	days	Time to clean between groups/cycles
Barn length	64	ft	
Barn width	24	ft	
Barn area	1536	ft^2	
Wall height	8	ft	
Barn volume	12288	ft^3	

Table 2.3: A sample set of sow barn model parameters

	Input/output	Units	Description
Adult Pigs	1500	pigs	Barn Capacity
Gilts	800	gilts/year	
Avg. Age Gilt	180	days	Average Gilt Age
Gilt Cycle	7	days	Time between delivery of gilts
Culled Sows	690	sows/year	
Cull Cycle	7	days	Time between sow culling
# Pig Deaths	110	pigs/year	Gilts minus culled sows
Piglets Surviving per Liter	10.5	piglets	
Death per liter	2.65	piglets	Stillborn plus mortality
Age Removed	20	days	Piglets removed from barn
Piglet Cycle	16	days	Piglet removal and re-insemination
Barn Length	298	ft	
Barn Width	111	ft	
Barn Area	33078	ft^2	
Wall Height	12	ft	
Barn Volume	396936	ft^3	

Table 2.4: A sample set of grow barn model parameters

	Input/output	Units	Description
Initial weight	50	lbs	Weight entering barn
End weight	275	lbs	Weight leaving barn
Pigs in per cycle	500	pig/cycle	Maximum 5,000
Pig death per cycle	20	pig/cycle	Pig deaths per barn cycle
Time to cleanout	5	days	Time to clean between groups/cycles
Barn length	114	ft	
Barn width	42	ft	
Barn area	4788	ft^2	
Wall height	8	ft	
Barn volume	38304	ft^3	

2.2.7.6 Processing

Proprietary production information from two swine processing companies in the US was used in combination with satellite imagery data to estimate the land footprint associated with pork processing facilities. The data were aggregated from more than ten facilities. Land inventoried included the space occupied by the processing facility as well as the surrounding property (i.e. parking lots). The environmental burden allocated to the finished pork product was 89% of the total facility land occupation. The remaining 11% was attributed to rendering products, based on reported average revenue derived from byproduct.

2.2.7.7 Packaging

The land footprint attributed to packaging resulted from the materials used to package a 4oz serving of pork. The packaging material included 8.8 g of polystyrene, 0.5 g stretch wrap, and 5 g of Vicose fibers used in the absorbent pad. Vicose fibers are derived from wood.

2.2.7.8 Retail

Retailers of processed pork typically package it for sale in-house. Therefore, land occupied by the retail store accounts for the space required for the process of packaging. Land occupation from the retailers was estimated based on a combination of information from the USDA, the Food Marketing Institute, and information obtained from the National Pork Board on the retail space utilization for pork products. Calculations were made using total sales volume, retail space, and the total area of the store allocated to pork from different retail venues such as supermarkets, mass merchandisers, and convenience stores. The resulting average was weighted based on each retailer's economic contribution to pork sales to determine the land occupation contribution from retailers of pork (Table 2.5).

Table 2.5: Retail sales volumes by type and contribution to land occupation

	m^2a/kg pork	Total Annual kg pork Sold	Total Annual Occupation (m^2)
Supermarket	0.00009551	11,182,211,429	1,068,036
Mass Merchandiser	0.00006178	3,524,858,053	217,780
Convenience Store	0.00016933	2,445,416,802	414,073
Total	0.00009910	17,152,486,283	1,699,889

2.2.7.9 Consumer

The land use associated with consumer use and disposal was negligible. Information on refrigeration and dishwashing processes associated with this phase were readily available, so they were included. Consumer waste was estimated to be 10% of the 4oz serving. Land occupied by consumer housing was not considered in the inventory, nor was landfill area accounted.

2.3 Results and Discussion

The land occupation required for production of 4oz of lean, boneless pork produced in the US for consumption was estimated to be 9.75 ft^2a (0.906 m^2a). The total amount of land used by the US pork industry was estimated at 15,000,000 acre*years (6.07 million ha*a). Figure 2.6 shows the land footprint contribution of each category of unit processes. Swine rations are by far the largest stage, comprising over 96% of land use in the supply chain, followed by the swine farm, packaging, and then processing. Retail and consumption stages had a negligible contribution.

The packaging category had a surprising contribution (Figure 2.6), slightly less than that of the swine farm itself. This was attributed to the absorbent pad. These pads are comprised of wood fibers, which have a significant land footprint due to the long production cycle of agroforestry (between 25 and 35 years depending upon management style and species).

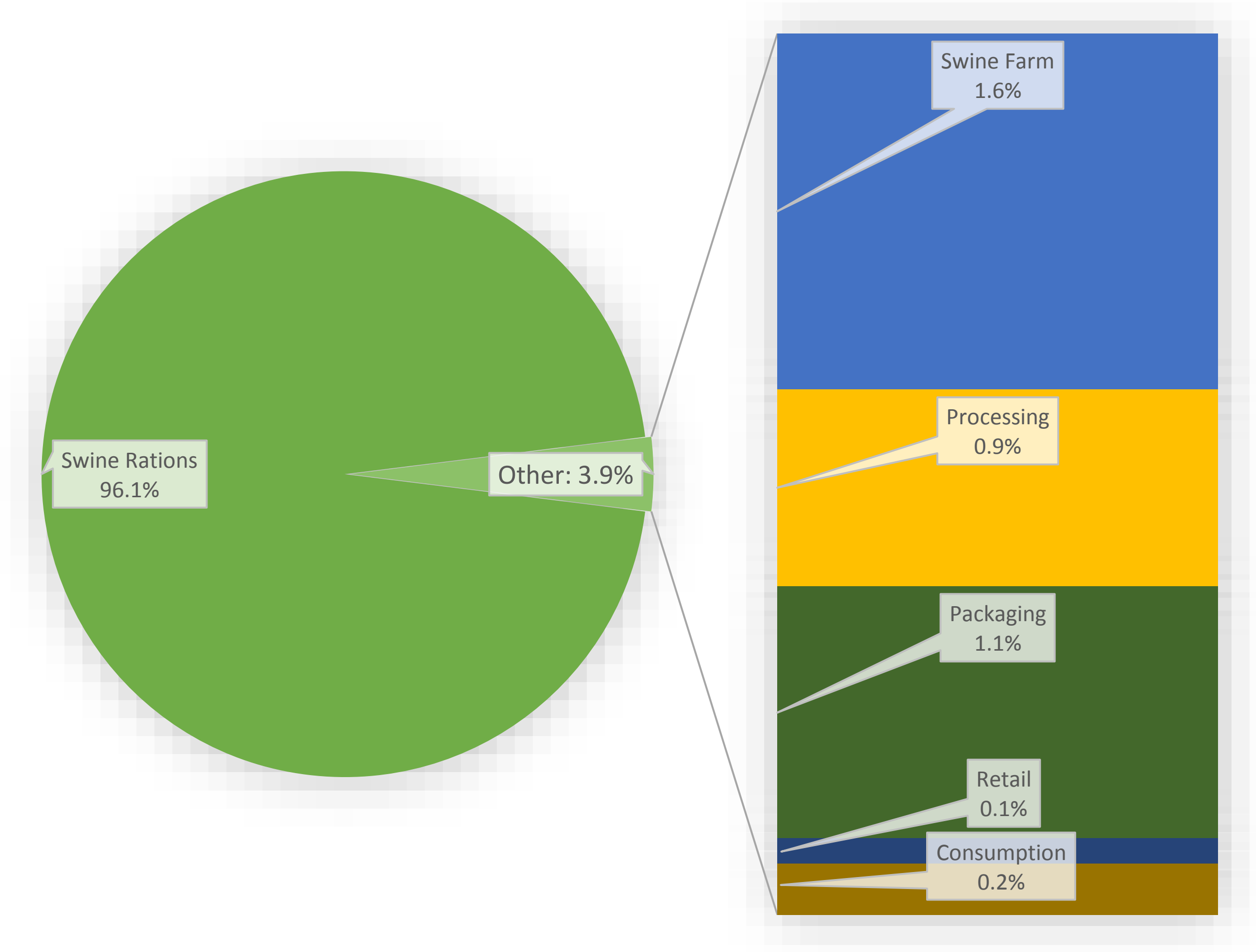

Figure 2.6: Percentage of total land use from "cradle to grave" in the production of US pork. Percentages represent a combined average of each of the ten regions, weighted by the total production in that region.

Further investigation of swine rations shows a majority of the footprint coming from the grow barn, followed by the sow barn, and then the nursery, as shown in Figure 2.7.

A sensitivity analysis was performed on the feed rations by running the model for each of the ten regions using two separate sourcing scenarios. This approached was adapted from Matlock et al. (2014). The first scenario used feed sourced from the region in which the pigs were produced. In the event that a particular region did not produce a particular feed ingredient, it was assumed that commodity crops were used. The second scenario assumed commodity crops were sourced exclusively. These two scenarios were referred to as Regionally Sourced Feed (RSF) and Commodity Sourced Feed (CSF), respectively.

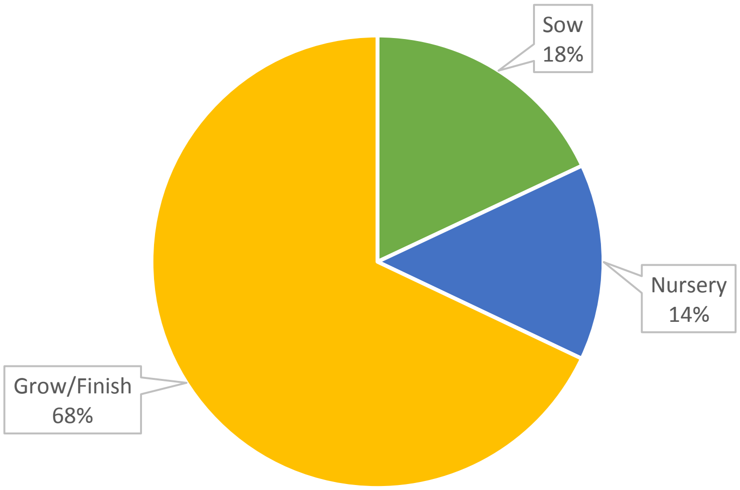

Figure 2.7: Breakdown of swine ration contribution by barn.

The CSF scenario showed minor variations across the ten regions, despite all sourcing the same feed. The differences between the two scenarios are presented graphically in Figure 2.8. These variations stem from the PPEC which accounted for regional climate effects on feed consumption and animal performance. These differences only contribute a variation of ± 1.0%. Much larger variation was seen in the RSF scenario. This is a result of the differences in corn

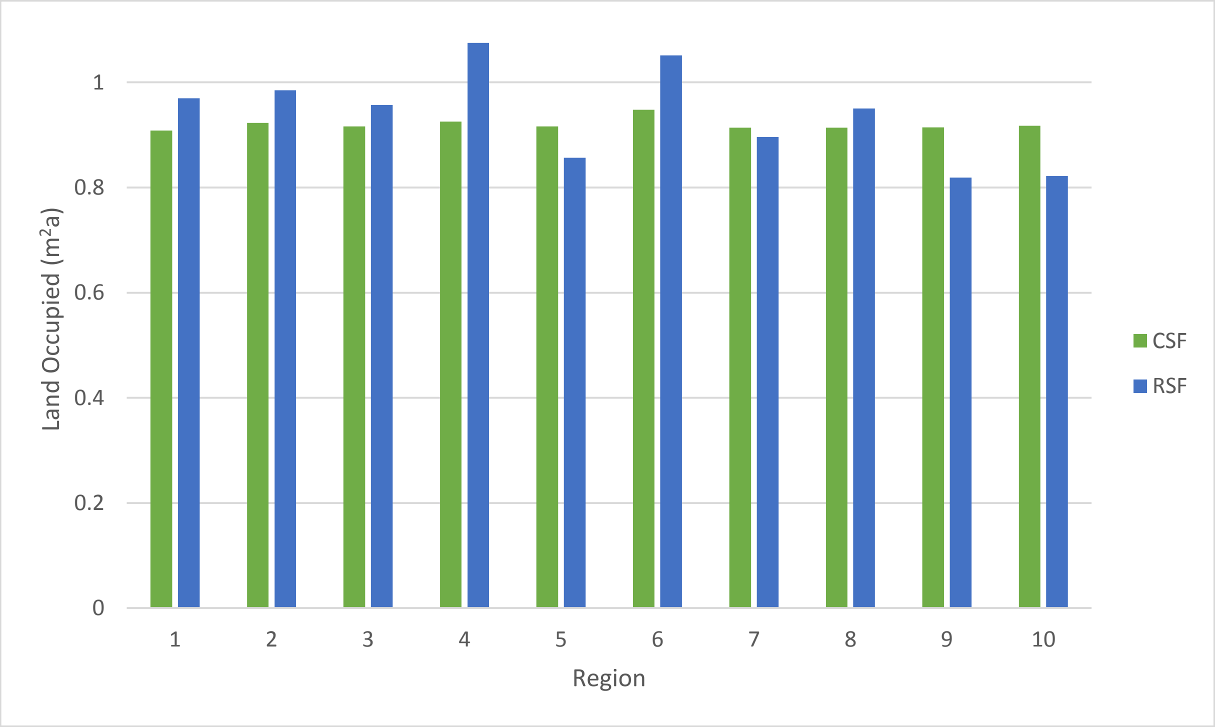

Figure 2.8: Land occupation required to produce 4oz of lean pork in the ten regions of US production using two feed sourcing scenarios.

and soy yields realized in each production region. The average variation was much greater than that of the CSF scenario, deviating ± 8.4%.

In order to more realistically depict sourcing practices of agricultural products used in swine feed, the proportion of commodity and regionally sourced feed was estimated for each region, as presented in Table 2.6. The assigned values were based on 2007 NASS census data for corn and soybean production in the regions. This approach follows the methodology developed by Matlock et al. (2014). Refer to that report for further detail. Figure 2.9 presents the regionally adjusted land occupation based on the proportion of commodity and regional ingredient sourcing given in Table 2.6.

Table 2.6: Production statistics and weighting percentages used for modeling real-world sourcing practices adapted from Matlock et al. (2014)

Region	Corn Production[1]	Soybean Production[1]	Commodity Sourced Feed	Regionally Sourced Feed
1	0%	0%	100%	0%
2	1%	0%	100%	0%
3	2%	2%	90%	10%
4	5%	6%	70%	30%
5	44%	44%	0%	100%
6	4%	5%	80%	20%
7	37%	34%	0%	100%
8	7%	9%	70%	30%
9	0%	0%	100%	0%
10	0%	0%	100%	0%

[1] *2007 NASS census data*

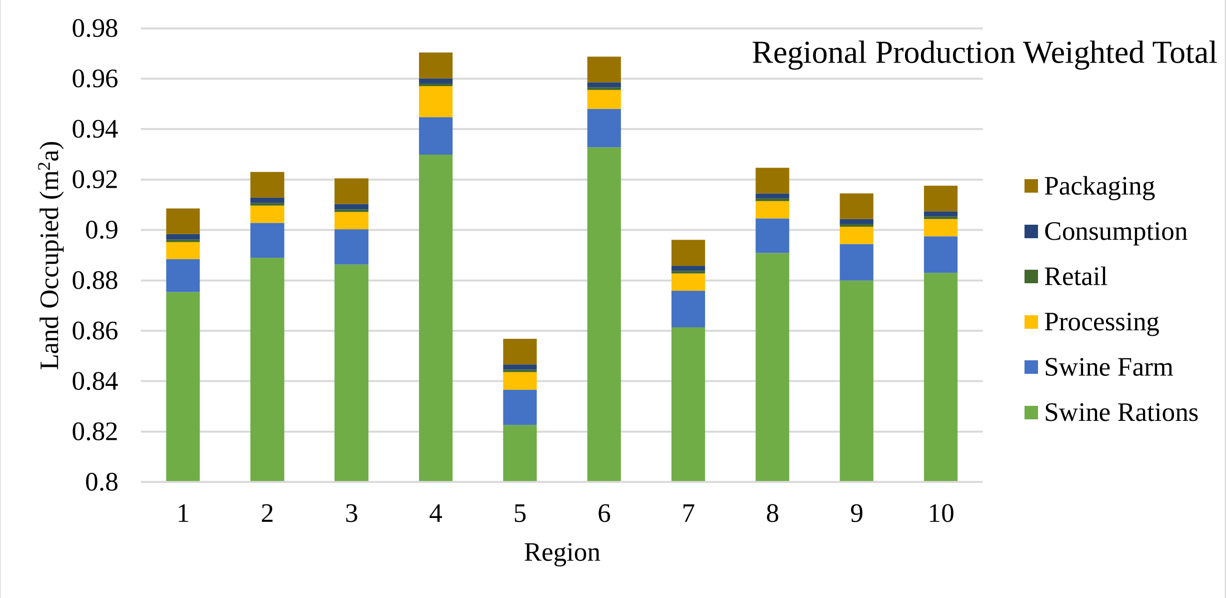

Figure 2.9: Land occupation by region for production and consumption of 4oz lean pork. Note: The Y axis begins at 0.8 m^2a to highlight the regional differences.

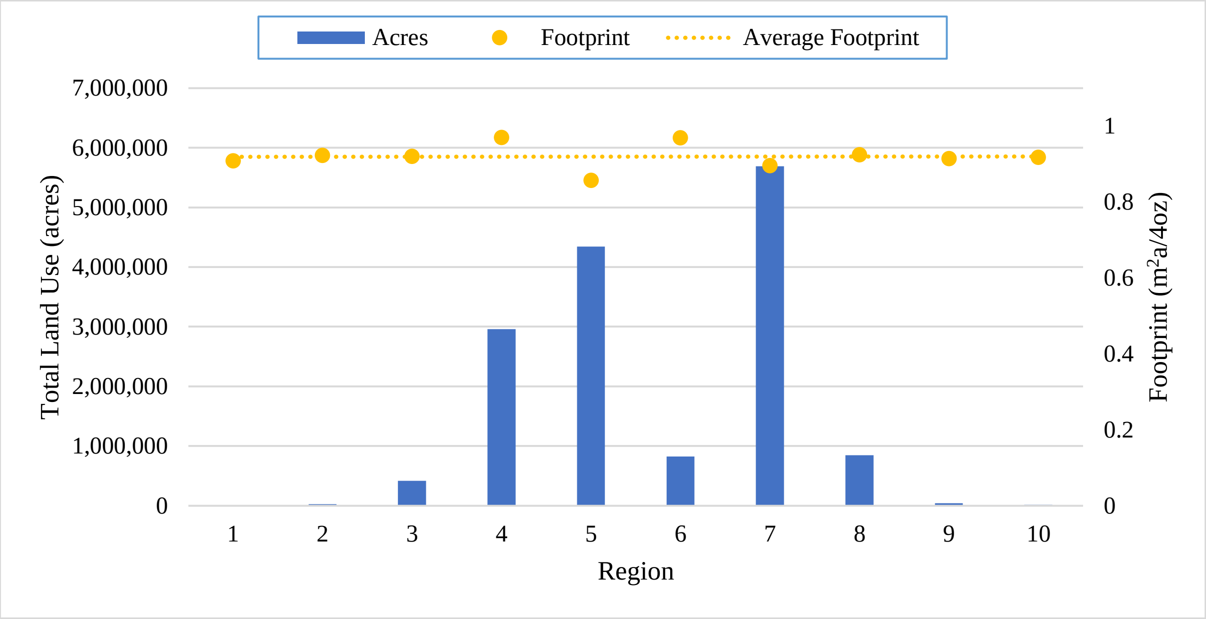

Figure 2.10: Regional contribution to the total land footprint of pork production in the US with footprint (land use per functional unit) overlaid.

The total land use in each region was estimated based on annual pork production (NASS 2012) in that region and presented graphically in Figure 2.10. In addition to total land use, each regional footprint has been overlaid along with the national average. Deviations from the national average are largely a result of differences in feed sourcing. Regions with footprints below the national average sourced feed from higher yielding areas of US corn and soy production

2.3.1 NASS Census 2012

In order to evaluate the effects of severe drought on land use, one scenario was run using 2012 NASS census data for region 5, and the results shown in Figure 2.11. Region 5 was chosen as a representative case, as it produces a majority of US swine. Prolonged drought in 2012 had serious impacts on corn and soy yields, resulting in an 8.8% increase in the land requirement for swine rations. This translated to an increase in the land footprint from 0.852 m^2a (9.17 ft^2a) to 0.931 m^2a (10.02 ft^2a) for region 5. When applied to US national production, this increase resulted in an additional 2 million acres required to produce the same amount of pork.

2.3.2 United States Comparison

At the time this report was written, only one LCA had been conducted on pork production in the US (Pelletier et al., 2010) with comparable system boundaries. Land use results were presented as ecological footprint, and thus not directly comparable. However, through personal communication with the author, raw inventory data was obtained that showed a land footprint of 3.53 m^2a per kg LW (17.2 ft^2/lb LW) at the farm gate, compared to 4.3 m^2a per kg LW (21 ft^2/lb LW) calculated by this study. The lower footprint was attributed to higher yields used for corn and soy in their model, as well as lower finishing weights. Another study (Stone et al. 2012) conducted an LCA on US pork production, but only considered inputs from post-gestation (29

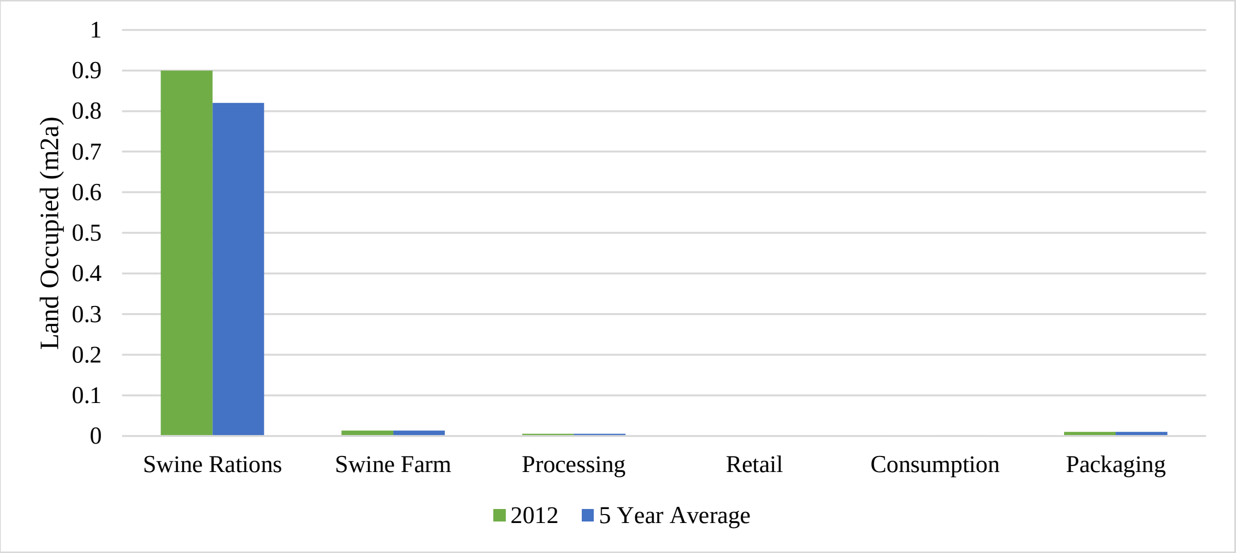

Figure 2.11: Land footprint comparison of a 4oz serving of lean, boneless pork prepared for consumption using five-year average yields (2004-2008) and 2012 yields.

kg) to market weight (118 kg for this study). Land occupation was not a focus of that study, however it was reported to be 1.65 m^2a / kg (8.05 ft^2/lb) live weight (LW), which, of course excludes the contribution from the sow and nursery phases as well as all post-farm impacts.

2.3.3 International Comparison

The estimated land footprint from this study is presented in conjunction with the six EU pork production studies evaluated in the literature review. The results are presented in square meters of land occupied annually to produce one kilogram of live swine at the farm gate in Figure 2.12. The EU studies were converted from boneless, retail meat to live weight using the conversion factors 0.729 (boneless to carcass) and 0.758 (carcass to live weight).

Stone et al. (2010) outlined several differences seen in EU production. Swine genetics and lower market weights were among them, as well as the use of other protein ingredients (i.e. peas) and less efficient ventilation systems. These differences were likely contributors to the higher footprints estimated by EU researchers, especially the differing protein sources.

2.4 Conclusions

It is clear that feed rations are the most significant contributor to land use in the production of pork for consumption in the US Feed consumed in the grow barn has the largest contribution, followed by the sow barn and then the nursery.

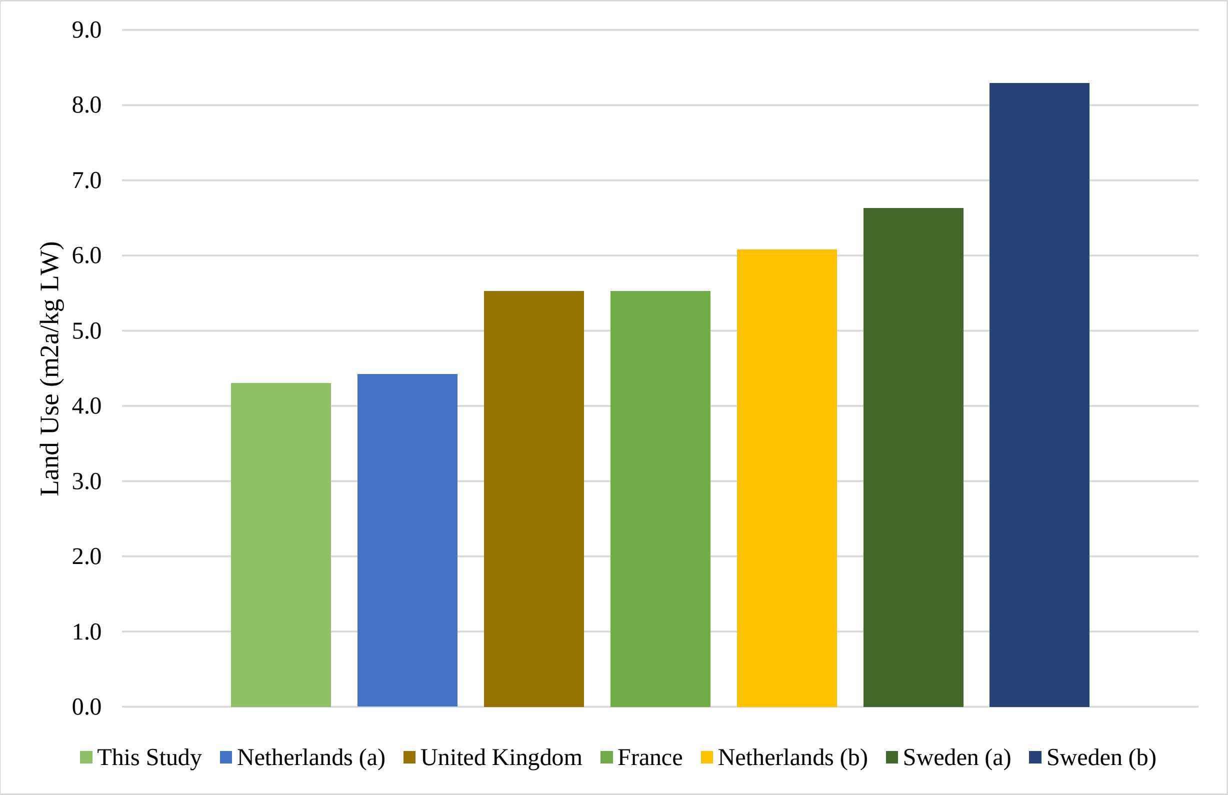

Figure 2.12: Land use per kilogram LW at the farm gate meat from six international land use LCAs. France: (Basset-mens and van der Werf 2005)*; Netherlands (a):* (Blonk et al. 2008)*; Netherlands (b):* (Zhu and van Ierland 2004)*; Sweden (a):* (Cederberg and Flysjö 2004b)*; Sweden (b):* (Strid Eriksson et al. 2004)*; United Kingdom:* (Williams et al. 2006)

Differences in climate across the ten regions have an effect on the amount of feed consumed on farm as animals eat less when temperatures are higher. This increases the amount of time it takes for them reach market weight, increasing the amount of feed consumed and thus the land footprint. This effect is captured by the PPEC and highlighted by regional differences in the CSF scenario. However, the source of corn and soy has a far greater impact, as demonstrated by the RSF scenario. The effects of sourcing largely masked those attributed to different climates.

The results of this study are comparable to the other similar US pork LCA. The different footprints estimated by this study and Pelletier et al. emphasize the impact of feed on land use. Further proof of this is demonstrated by the comparison with 2012 yields.

The results are also within reason, although lower, than those from similar assessments conducted in the EU. Differences in the EU and US swine industry practices and feed composition are likely to account for greater land use associated with production in the EU.

An analysis performed with amplified focus on live swine production will serve to quantify the impact of different ration compositions on land use in US pork production.

3 Detail-Level Life Cycle Assessment

3.1 Introduction

Global growth and development coupled with pressures arising from a growing global middle class consuming more animal protein in their diet place a high demand on arable land in the effort to feed an expanding population that now totals over 7 billion people, and is expected to approach 10 billion by 2050 (Tilman et al. 2011). The impact of these forces on the capacity of land to provide ecosystem services and support natural assets like biodiversity, are not well understood. Quantifying the human influence on terrestrial resources is critical to managing production risks and to guarantee the sustainability of our food systems.

Pork is the most widely consumed meat in the world, representing approximately 37% of global meat consumption (FAO 2013). The US is one of the world's leading pork producers, second only to China. In 2012, the US swine industry accumulated sales of $22.5 billion, representing 6% of all agriculture sales in the US. The farms producing a majority of these pigs are primarily located in the Midwest, with 5 of the top 10 producing counties in Iowa. Other Midwestern states such as Minnesota and Nebraska also have large pig sales. Production is centered in this region largely because it is the source of the majority of corn production, a primary ingredient in swine feed. With the average market hog consuming nearly ten bushels of corn in its lifetime, and US pigs in inventory averaging 65 million at any given time over the past five years (USDA 2014), the land use associated with production of the main energy animal feed, corn, is significant.

3.2 Objectives

The National Pork Board (NPB) commissioned the Center for Agricultural and Rural Sustainability at the University of Arkansas (UA) to perform a life cycle assessment (LCA) of the United States pork production in order to quantify land use of US pork production.

This report presents the findings of the detailed assessment, including a preliminary assessment of tradeoffs, accounting for all relevant land occupied from "cradle to farm gate" in the production of pork in the US The phrase "cradle to farm gate" refers to all processes required to produce live swine ready for transport to the abattoir.

The LCA methodology was chosen for its ability to quantitatively analyze potential impacts associated with complex systems. A LCA consists of four iterative phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The resulting analyses are intended to inform pork producers, and to communicate with interested third parties.

3.3 Materials and Methods

The following sections outline the four phases of LCA as applied to this study.

3.3.1 Goal and scope definition

The goal of this task was to conduct a detailed LCA of the US pork production supply chain to quantify land use requirements and provide a benchmark for future assessments. The intended audience for this assessment is US pork producers, as well as interested third parties. The purpose is to identify aspects of production that contribute significant environmental impacts as a result of their associated land use. Identification of processes contributing to high environmental impacts often highlights opportunities for gains in efficiency, which can increase profitability and lead to more sustainable production practices.

3.3.2 System Boundaries

The scope of this study is from cradle to farm gate. The system boundaries for this assessment are intended to include all relevant process flows required to produce 1kg of live weight of a market ready animal: from fertilizers used in the production of swine feed ingredients to material components of the swine farm's infrastructure. While the principal focus of this report is land use, we have also included an assessment of trade-offs, which may arise when producers use ration manipulation as a mitigation option. Figure 3.1 diagrams the major supply chain stages included in the trade-off assessment in addition to the land use assessment. Land occupied by pesticide and fertilizer production facilities are included, as well as land requirements associated with raw materials used to create swine barns.

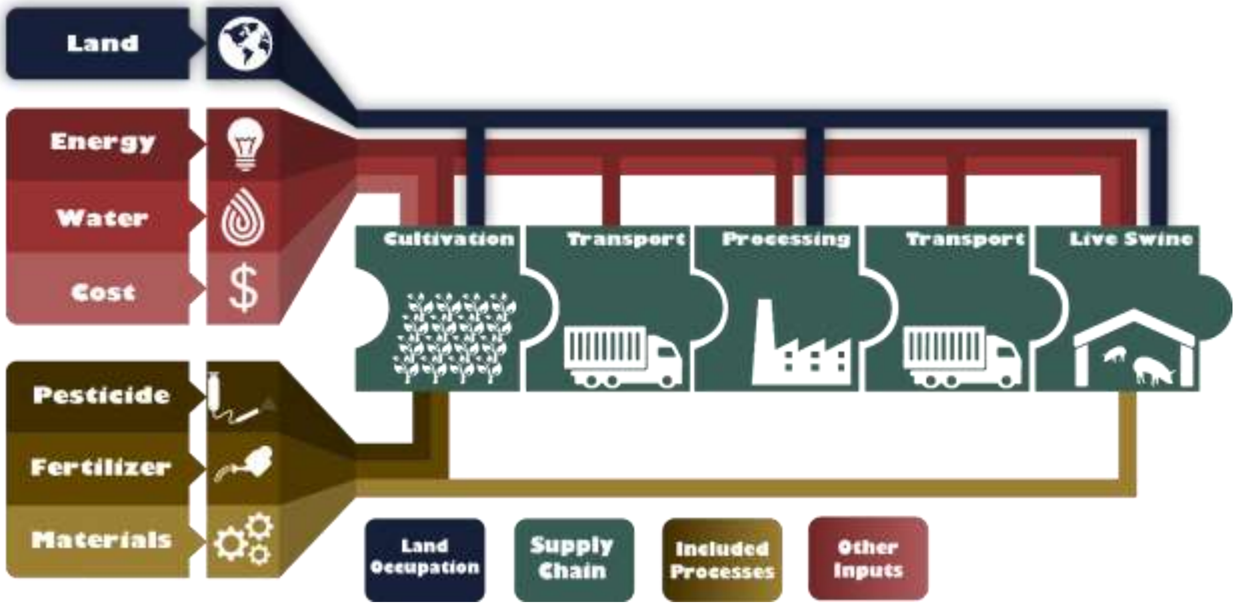

Figure 3.1: Process flow diagram illustrating the system boundaries for this LCA. Inputs in red are considered when comparing the tradeoffs associated with alternate ration formulations.

3.3.3 Functional Unit

The functional unit for this LCA was defined as one kilogram (2.2 pounds) of live swine at the farm gate, ready for transport to the abattoir.

3.3.4 Allocation

In situations where an input was a by- or co-product of another process, an allocation of the environmental burden was established. The International Organization for Standardization recommends system separation and then using a system expansion approach for allocation whenever possible. System expansion requires detailed assessment of markets to identify substituted products and was considered to be beyond the scope of this project. This assessment allocated product burdens of system inputs (primarily soymeal and DDGs) according to their economic value. A majority of the allocation values used in this assessment are from the work of Thoma et al. (2011). Several non-conventional animal feeds were also used in scenario analyses. For those feed ingredients not previously used in LCAs conducted for the NPB, the background database allocation was adopted without modification (for most cases this is an economic allocation, and thus consistent with the approach taken for allocation decisions for this project) (EarthShift 2011; Blonk Consultants 2014; Weidema et al. 2013)

3.3.5 Key Assumptions

All crops used for feed rations in this assessment were assumed to be the only crop grown on a given area of land each year. That is to say, double cropping was not considered. In addition, we did not make distinction for different potential crop rotation sequences. For specific situations where these practices are employed, the land use may be lower than the average values reported here.

3.3.6 Life Cycle Inventory

3.3.6.1 Regions of Production

Of the ten pork production regions defined by the USDA, regions 4, 5, and 7 were chosen to cover a range of production practices and to capture potential effects of differences in climate. Regions 4 and 5 cover the Midwestern US and Region 7 covers the Southeast. In combination, these three regions represent 86% of swine production (Figure 3.2) in the US

One county from each region was chosen to be the archetype, providing climate data and production practices typical of the production area. Table 3.1 shows the archetypal county from each region.

Table 3.1: Representative counties modeled and total production for each region.

Region	Total Production (1000 head)	Representative State	Representative County
4	38,840	NC	Wake
5	57,053	IN	Jasper
7	74,719	IA	Hardin

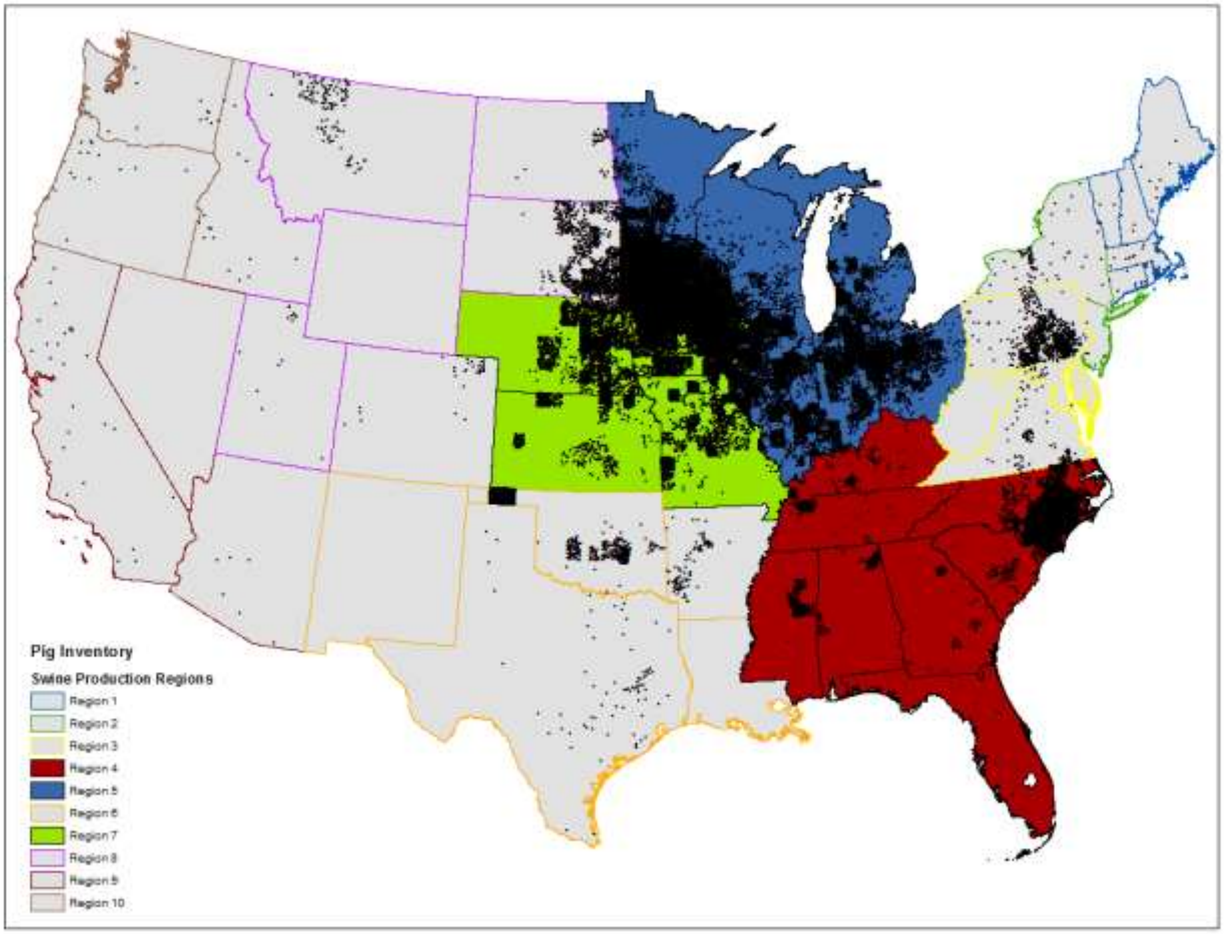

Figure 3.2: National swine production and the three regions assessed in this study. Each black dot represents 1400 head of swine (USDA NASS, 2012).

3.3.6.2 Production Practices

Each stage of production was assumed to occur on the same farm, in a distinct building, representing a discrete life-stage for the pigs. All production buildings were assumed to be tunnel-ventilated and utilize deep pit manure management systems; with the exception of region 4, where a subfloor flushed to anaerobic lagoon system was modeled. There is no evidence in the literature that the choice of manure management system has an effect on the land area required for swine production as (see below: §Swine Farm and §Sensitivity Analysis).

3.3.6.3 Phases of Production

The first production phase is denoted as Sow Barn. Sow barns were modeled to house gestation, farrowing, and lactation stages. All sow barns were assumed to provide 22.1 ft^2 (2.05 m^2) per pig-space.

The second phase of production was denoted Nursery Barn. Nursery barns were modeled with 500 piglets entering for each cycle that were raised from 12 to 50 pounds (5.4 to 22.7 kg), providing an average of 3.1ft^2 (0.29m^2) per pig-space.

The final phase of production was denoted Grow/Fin Barn. Pigs in this phase were grown from 50 to 275 pounds (22.7 to 125 kg) – the market weight for this study. The barn provided an average of 9.6ft^2 (0.89m^2) per pig-space.

3.3.6.4 Production Demographics

Input parameters relating to demographics such as mortality rates were adopted from previous LCAs for the NPB (Thoma et al., 2011, 2013; Matlock et al., 2014).

3.3.6.5 Feed Scenarios

The results of Task 2 of this project indicated that 96% of land occupied to support production and consumption of pork in the US is attributed to production of animal feed used in swine rations. Thus, seven different feed scenarios were developed in order to assess the impact associated with various swine ration formulations.

Baseline Scenario

The swine ration from Task 2 was designated as the baseline for comparison. It was developed for previous LCAs conducted for the NPB. It is based on literature values and communication with industry experts and nutritionists in an effort to represent a typical feed ration used by US pork producers.

Least Impact Scenarios

Four feed scenarios were created using the Windows-based User Friendly Feed Formulation (WUFFDA) linear program model (Pesti et al. 2008). The WUFFDA model is an Excel-based software tool originally developed to teach poultry and swine nutrition. It consists of a series of spreadsheets that contain information on feed ingredients including price, nutrient composition, and minimum and maximum inclusion rates. The model uses the Solver feature within Excel to find the least-cost solution for feed formulation that meets specified nutrient requirements for different stages of growth. It was modified to calculate a feed scenario that minimized land use rather than cost. Additional, nutritionally equivalent, feed scenarios were created as strategies to lower cost, climate change impact, and water use. These scenarios were incorporated into this assessment in order to highlight the challenges and tradeoffs faced by swine producers when formulating rations in the context of minimizing environmental impacts of land, water, and energy use.

Along with the 27 feed ingredients from the baseline scenario, ~50 additional protein and energy feed ingredients that have been reported to be used by the US pig industry were added to the WUFFDA model to broaden the options for selection of ingredients needed to meet the nutrient and environmental or cost requirements. Each of the feed scenarios was compared to the baseline.

The WUFFDA model requires cost, land, water, carbon, and energy footprints in addition to nutrient characteristics of all feed ingredients. In order to create single-objective least cost, carbon, land, and water use rations, additional WUFFDA models were created using environmental impact (instead of the cost) as the objective function for minimization, while still meeting the nutritional requirements for each stage of animal growth. Animal feed ingredients and their nutrient composition were obtained from a compilation conducted by Burek et al. (2014). The nutrient composition of the feed ingredients is based on the US National Research Council pig nutrient requirements (National Research Council 2012). The UA Department of Agricultural Economics & Agribusiness collected the average prices of feed ingredients. The minimum and maximum nutrient requirements for dry matter, metabolizable energy, protein, calcium, phosphorus, and amino acids were adopted from the National Swine Nutrition Guide (USPCE 2010) as suggested by the UA nutritionist. Mineral requirements for potassium, manganese and zinc remained as provided by the WUFFDA and were verified using requirement equations for starter and grow-finisher (Pesti et al. 2008; National Research Council 2012). The US pig nutrient requirements guidelines do not provide recommendations for ether extract, C18:2, sodium, chlorine which were adopted from WUFFDA (National Research Council 2012; Pesti et al. 2008; USPCE 2010). To ensure proper amounts of amino acids (DL-methionine, L-lysine-HCl, and L-threonine), minerals (calcium phosphate, copper sulfate, limestone, and zinc oxide), and vitamins (grow-finish vitamin premix, nursery vitamin premix, trace mineral premix, and vitamin E) in a ration, they were set at fixed values based on typical inclusion rates obtained from the nutritionist. Values for carbon footprint, land occupation, and water use for each ingredient were calculated using SimaPro 8.3 software on a per kilogram of feed ingredient basis (PRé Consultants 2014; Burek et al. 2014). When existing data were unavailable in SimaPro, unit processes were created or modified to create the US national average footprints using USDA NASS census data.

The four scenarios were labeled as follows: Least Cost Scenario (LC), Least Carbon Footprint Scenario (LCF), Least Land Footprint Scenario (LLO), and Least Water Use Scenario (LWU). Table 3.2 lists all feed ingredients individually contributing more than 1% of the total ration. The four ration scenarios are hypothetical and represent guidelines for developing realistic, sustainable, and cost-effective swine rations that producers will be able to incorporate into their production system.

Reduced Crude Protein Scenarios

Two additional feed scenarios were adopted from experiments conducted by researchers from the UA in collaboration with Purdue and Virginia Tech University to determine the effects of substituting synthetic amino acids to replace crude protein in swine rations for wean-to-finish facilities (Apple et al. 2013). Minor modifications were made to the reported rations for consistency with the PPEFC requirement that the percentages sum to 100%. Production in wean-to-finish facilities does not include sows. Therefore, neither the control nor the optimal ration adopted from the synthetic amino acid study included sow rations. Sow barn feed rations from the baseline scenario were used when modeling these scenarios.

Least Crude Protein Control Scenario (LCPC): This is the same feed ration used as the control in the synthetic amino acid study. Major differences in this feed scenario from the baseline include three nursery phases (versus only one in the baseline), and in general, higher quantities of soybean meal and slightly lower quantities of corn grain. In addition, since this was an experimental feed ration, the measured values for average daily gain (ADG) and feed conversion ratio (FCR) were enforced to the calculator.

Table 3.2: Major ration components of the four "least scenario" rations formulated by the WUFFDA model

Ingredient	LCF	LC	LLO	LWU
Alfalfa Meal	-	-	-	8.6%
Barley	-	-	-	13.7%
Blood Meal, Spray Dried	-	-	2.9%	-
Blood Plasma	-	-	4.4%	1.5%
Canola Meal, Expelled	-	-	-	12.8%
Corn DDG	-	11.5%	19.1%	-
Corn Gluten Feed	-	-	13.0%	-
Corn, No. 2	-	-	2.3%	-
Fat (A/V Blend)	-	-	-	3.8%
Fat, Beef Tallow	2.3%	-	4.2%	-
Feather Meal	-	-	1.9%	3.4%
Fish Meal Combined	-	-	7.6%	7.6%
Flaxseed Meal	-	-	-	12.0%
Meat and Bone Meal	-	-	7.5%	-
Molasses, Sugar Beets	3.4%	-	3.4%	-
Molasses, Sugarcane	3.4%	-	3.4%	-
Peas, Field Peas	-	-	-	27.6%
Rice Bran	-	-	19.9%	-
Sorghum	-	10.5%	-	-
Soybean Hulls	7.0%	-	-	-
Soybean meal, 48%	28.9%	8.4%	5.1%	4.7%
Soybeans, High Protein, Full Fat	7.1%	-	-	-
Wheat Middlings	22.1%	-	-	-
Wheat Shorts	2.5%	-	-	-
Wheat, Hard Red Winter	19.7%	65.6%	-	-

Optimal Synthetic Amino Acid (LCP): This feed scenario simulated the “optimal” synthetic amino acid substitution used in the study. For the nursery barn, we adopted the ration used in treatment 4 (of 5) from the experiments performed at UA (Maxwell et al. 2012). Treatment one was the control (used as the base case, described above). Treatment four was chosen as the study found that this was the maximum level of lysine HCL that could be substituted for crude protein without contributing to significant decreases in ADG and average daily feed intake (Maxwell et al., 2012; Apple et al., 2013). The same criterion was used in selecting the ration used for the grow/finish barn simulations.

3.3.6.6 Feed Sourcing

All seven feed scenarios were assessed using national commodity averages for production practices and crop yields. Regional production data was available for corn and soy-based products, but the national commodity averages were used to provide consistency across all ingredients. The Baseline, LCPC, and LCP ration scenarios closely resemble a typical swine diet used by US pork producers. Therefore, these scenarios were also assessed to include the impacts associated with sourcing feed within the region of swine production.

Regional production analysis assumes corn, DDGs, and soybean meal were sourced partially or fully within each region of swine production. The 2012 USDA NASS census reported that approximately 80% of the nation's corn and soy were produced in regions 5 and 7. For those regions, it was assumed that 100% of those feeds were sourced from within the region. Approximately 5% of US corn and soy were produced in region 4. Therefore it was assumed that 30% of those feeds were sourced from within the region and 70% were commodity-sourced. The ratio of regional to commodity feed sourcing was determined by Matlock et al. (2014) and was also used in Task 2 of this project. The cost of feed was assumed to be the same in all regions.

Several feed ingredients used to formulate the least-cost/footprint rations were not included in previous LCAs conducted for the NPB. For these ingredients, we used preexisting unit processes in SimaPro. In the event that a unit process representing US production was not available, European ones were used with updated values for crop yield based on national commodity averages.

3.3.6.7 Swine Farm

In order to account for land use/occupation by the swine farm itself, the following regression equation relating land use to annual production capacity was calculated using data from two conventional swine facilities modeled by Lammers et al. (2009).

$$LU = 1.2502P + 5367$$

Where LU is land use/occupation by farm operations in square meters and P is number of pigs produced annually. In some states regulations exist which require that manure storage be a minimum distance from neighbors; however, there is no requirement that the swine farm owns all the land necessary to provide this offset distance, thus there is no clear correlation between the areas required for different manure management systems. While it is anticipated that outside lagoons require additional land compared to deep pits, the sensitivity of land use/occupation to the live swine production facility area is low (see §Sensitivity Analysis). Further information on the facilities modeled can be found in the literature review from Task 1.

Building materials required for construction of each barn were adopted from the work of Thoma et al. (2011). Barns were assumed to have a lifespan of fifteen years as suggested by Lammers et al. (2010) and land use impacts associated with their material inputs were amortized over this period of time.

3.3.7 Model Development

The seven rations and all necessary input parameters were entered into The Pig Production Environmental Footprint Calculator (PPEFC), a modeling program to simulate pork production (National Pork Board 2015). The calculator estimates swine growth and resource use based on user input data such as geographic region of production (in order to account for the effects of different climates), feed ration composition, and type of production facilities. For this study, we created three models within the PPEFC: one for each of the sow, nursery, and grow/finish phases of production.

All seven scenario rations were simulated with the PPEFC for each region of production. The results produced by the calculator were then transferred to SimaPro 8.3 software (PRé Consultants 2014). All 21 combinations, presented in Table 3.3, were then assessed based on four categories: carbon footprint (also referred to as climate change impact) (kg CO_2 equivalent/kg live swine), water use (m^3 H_2O/kg live swine), cost of feed (USD/kg live swine), and land occupation (m^2a/kg live swine). The impact category carbon footprint did not account for contributions from land use change, because for US production land has been under continuous cultivation for many decades. A national average land use footprint for US production was also assessed by combining the results of the three regional scenarios, weighted by head of swine produced annually in each region. Figure 3.3 shows the entire modeling process as a flow chart.

Table 3.3: Scenario modeling matrix.

Feed Scenario	Production Region	Phase of Production	Impact Category/Inventory
Baseline	Region 4	Sow	Land Occupation
LCF	Region 5	Nursery	Water use
LC	Region 7	Grow/Fin	Feed Cost
LLO	National Average		Carbon footprint
LWU			
LCPC			
LCP			

3.3.8 Life Cycle Impact Assessment

The resulting resource use and emissions to the environment catalogued in the life cycle inventory were characterized for their GWP using the characterization model outlined by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) over a 100-year time horizon (Forster et al. 2007). Characterization factors (known as global warming potentials -GWP) provide a common metric for all the gases that contribute to the radiative forcing which affects global temperatures. IPCC uses kilograms of carbon dioxide equivalent (kg CO_2e) as the common metric and provides a list of GWP for a range of different gases (Myhre et al. 2013; Forster et al. 2007). While land use is the primary category for this assessment, carbon footprint – along with water use and feed cost – were included in the results

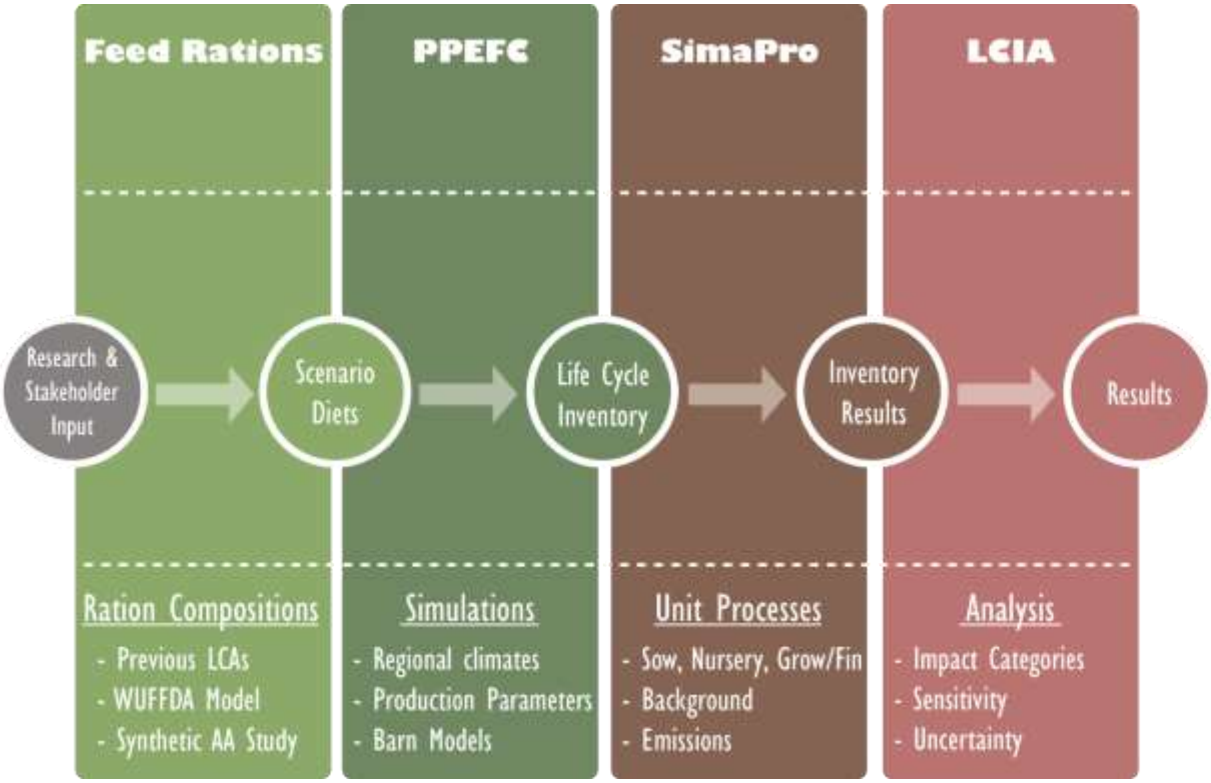

Figure 3.3: Process flow chart outlining the modeling process.

in order to assess potential tradeoffs associated with formulating a feed ration to achieve simultaneous cost and environmental impact reduction.

3.4 Results and Discussion

Results for water use, feed cost, carbon footprint, and land occupation are shown in Table 3.4. The values indicate the national average for each ration scenario. The least-cost/footprint rations formulated by the WUFFDA model resulted in better performance compared to the Baseline in their respective categories. The greatest improvement was seen in the Least Water Use ration for the category of water use. For the reduced crude protein rations, increased levels of synthetic amino acids reduced the ration cost and land occupation but resulted in increases in carbon footprint and water use.

3.4.1 "Least Cost/Footprint" Scenario Rations

The WUFFDA model created nutritionally equivalent least-cost/footprint rations in each category. The current implementation of the WUFFDA model used is only capable of optimizing one objective at a time. Although this approach identifies a ration with reduced footprint or cost compared to the Baseline ration, there can be significant increases in other impact categories. This is shown most clearly by the Least Water Use ration, which results in a 73% decrease in water use compared to the Baseline. However, that ration scenario resulted in increases in cost and land occupation. The decrease in water use can be attributed to the inclusion of rotational

Table 3.4: National average values for the ration scenarios and their associated impacts by category. In each column the best (green) and worst (red) rations are highlighted, demonstrating the trade-offs between environmental categories and cost.

Scenario	Carbon Footprint (kg CO_2e per kg live swine weight)	Water Use (m^3 H2O per kg live swine weight)	Feed Cost (USD per kg live swine weight)	Land Occupation (m^2a per kilogram live swine weight)
Baseline	2.87	0.24	0.90	4.22
LCF	2.01	0.14	1.09	6.02
LC	2.89	0.24	0.88	7.83
LLO	2.56	0.10	1.41	1.48
LWU	2.67	0.06	1.73	9.68
LCPC	2.77	0.21	0.94	4.47
LCP	3.02	0.23	0.83	3.72

and cover crops such as field peas, rapeseed, and alfalfa. These crops are primarily grown in the Northern Great Plains region and typically receive irrigation only as a supplement to rainfall – if at all (Scherer et al. 2013). Unlike crops that require more frequent irrigation to provide consistent yield, those crops selected by the WUFFDA for this ration have high variability in yields according to USDA (USDA 2014) data resulting in lower national average yield, and thus in higher average land occupation.

The Least Land Occupation ration also resulted in a significant decrease in land occupation over the Baseline. When considering this ration, the land occupation associated with producing the functional unit was less than half that of the Baseline, roughly four times less than that of the Least Cost and Least Carbon Footprint, and six times less than the Least Water Use ration. This reduction is attributed to selection of crop derivatives and byproducts (e.g. rice bran), which are generally less expensive than the agricultural products from which they are derived. Since byproduct environmental burdens were allocated on an economic basis, low-cost byproducts are assigned a smaller land footprint. Because this allocation assumption significantly affects the results, a sensitivity analysis was conducted using mass and energy as alternative methods of allocation. Results from the sensitivity analysis are presented in a subsequent section of this report. Allocating by-product burdens according to economic value at the point of production does not always result in an impact reduction for all categories. For example, carbon footprint may increase for byproducts if they receive further processing that requires energy (e.g. drying of distiller's grains), thus accruing the burden of additional GHG emissions, which are not subject to the economic allocation. This tradeoff is demonstrated by the Least Land Occupation ration, which resulted in a 43% increase in carbon footprint over the Baseline. Table 3.5 displays each scenario ration's change from the baseline for each of the four impact categories.

The Least Carbon Footprint ration showed reductions in the carbon footprint category through the inclusion of wheat and wheat byproducts. Allocation by mass, energy, or economics results in 70% or more of environmental burdens attributed to flour, thus leaving wheat derivatives like

Table 3.5: Percent change from the baseline for each of the 4 least scenario rations per functional unit. Negative numbers represent a decrease in impact from the baseline. Values in boxes along the diagonal represent the impact category for which the scenario ration was optimized.

Scenario	Carbon Footprint	Water Use	Feed Cost*	Land Occupation
Least Carbon Footprint	-30%	-42%	21%	43%
Least Water Use	-7%	-73%	92%	130%
Least Cost	1%	2%	-2%	-86%
Least Land Occupation	-11%	-56%	56%	-65%

*Cost refers only to the cost of feed rations

bran, middlings, and shorts to be relatively low impact ration components in terms of carbon footprint and water use. However, with wheat driving a majority of the ration, the categories feed cost and land occupation were negatively impacted. Land occupation increased over the baseline because the average wheat yield in the US is approximately half that of corn. Wheat has also experienced a 30 million acre reduction in harvested land area in the past three decades, while global demand for wheat has increased, thus causing an increase in cost.

Of the four least cost/footprint rations, the Least Cost ration resulted in the smallest gain over the baseline for its category. This is not surprising as cost is a major contributing factor in ration formulation by swine producers. The Least Cost ration was the only one to produce a reduction in cost. The WUFFDA model formulated this ration with high quantities of hard red winter wheat, which has a slightly higher cost than corn but 64% more protein. The higher protein content of wheat reduced the reliance on more expensive protein feeds like soybean meal. Impacts increased for all other categories for this ration.

3.4.2 Reduced Crude Protein Rations

The Least Crude Protein Control (LCPC) and Least Crude Protein (LCP) rations were adopted from a research trial. The LCP ration substituted soybean meal, the principal source of crude protein, with elevated levels of synthetic amino acids. As mentioned above, the authors of that study found no significant detriment to growth rate and pig performance when fed the LCP ration as compared to the LCPC ration (Apple et al. 2013).

Regional LCI feed data were available in addition to that for commodity feed used in the scenario assessment reported above. Therefore, results from the least crude protein rations are divided into two sections: national production and regional production.

3.4.2.1 National Production

National production results were determined as a production (total head) weighted average of the results from each of the regions. The LCI data were developed using a five-year national average for corn and soybeans using USDA datasets. Swine production characteristics were produced from the PPEFC and include the effects of climate on swine operations.

The results of this impact assessment showed decreased land occupation and feed costs associated with producing swine fed with the LCP ration over the LCPC ration. On the other hand, higher impacts were attributed to the LCP ration for water use and carbon footprint. The composition of soybean meal, corn, and amino acids in these two rations explains the differences in associated environmental burden. References to corn do not include DDGs. Although DDGs are derived from corn, their contribution to the total in both rations was the same.

The LCP ration was composed of more corn, which was added to the ration to compensate for some of the lost energy derived from soybean meal. Corn is cheaper and higher yielding than soybeans and that drove the reductions in feed cost and land occupation versus the LCPC ration. However, higher levels of corn in the LCP ration had the reverse of effect on water use. Because soybean meal is a byproduct of processing soybeans for oil, it received an allocated burden, which did not cause a large enough reduction in consumed water to offset the increase from additional corn in the ration.

A significant carbon footprint was attributed to amino acid production, and higher inclusion rates in the LCP scenario were the primary drivers increasing the carbon footprint. Major ration component contributions from the two ration scenarios are directly compared across the four categories in Figure 3.4 through Figure 3.7.

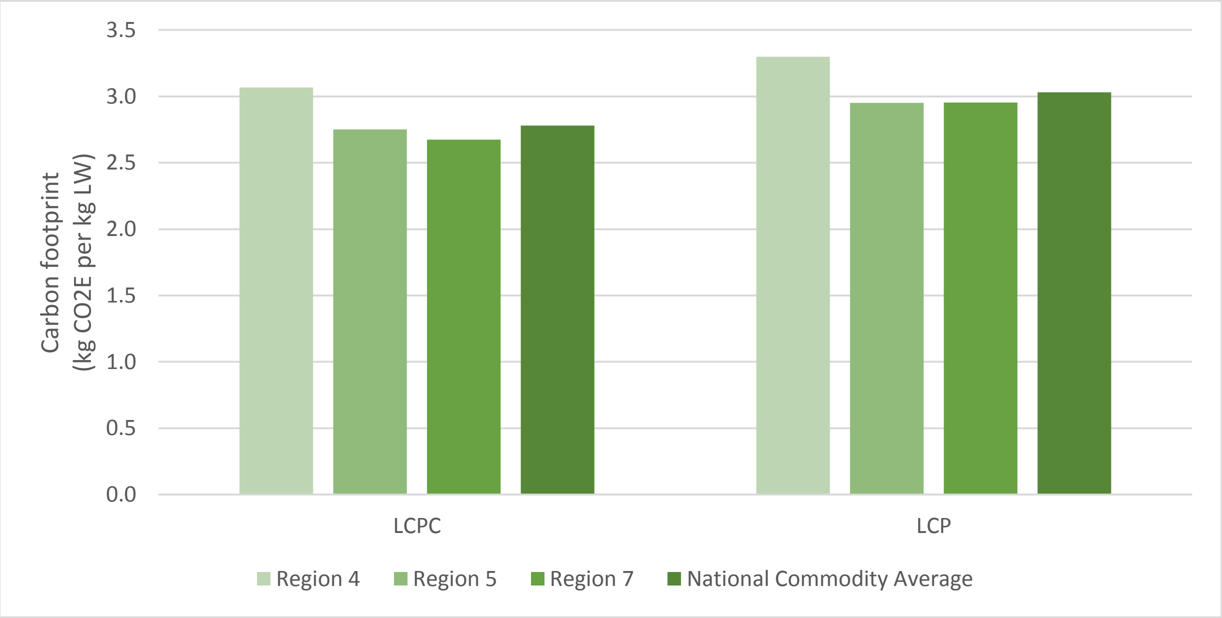

Figure 3.4: Carbon footprint for each region of production and as a national average using commodity feed.

3.4.2.2 Regional Production

Across all four impact categories, region 4 had the highest potential environmental impacts. Several factors influence this result. First, regions 5 and 7 have higher yields for corn and soy

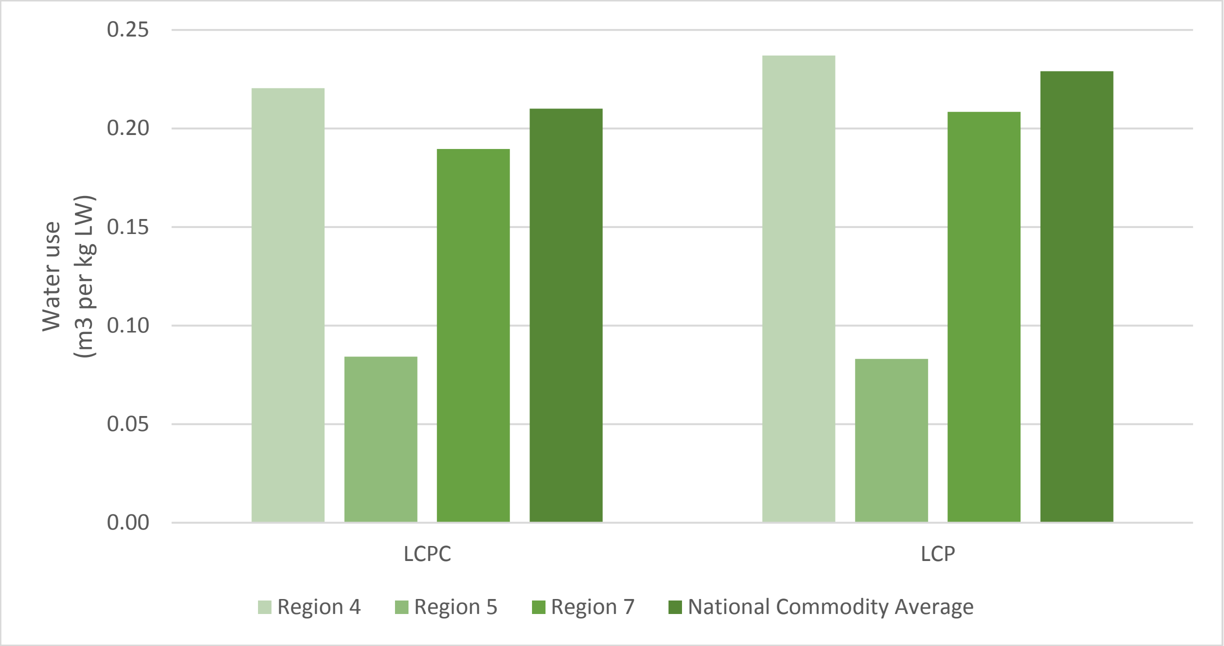

Figure 3.5: Water use for each region of production and as a national average using commodity feed

than the commodity average, resulting lower impacts per kg harvested. Second, the climate in region 4 tends to be warmer than the other two regions. In warmer climates pigs consume less food each day, which prolongs the time it takes to reach market weight. This effect reduces the feed conversion ratio and results in greater impacts associated with the functional unit. Finally, the manure management system in region four was modeled as a subfloor plus lagoon rather than a deep pit, which has larger greenhouse gas emissions.

Pork production in region 5 was shown to require less water than production in the other two regions. This can be attributed to crop production in the region, which generally requires less irrigation than other regions in the US

Excluding water use, the LCPC ration produced swine with lower impacts in region 7 than in region 5. However, the opposite was true of the LCP ration. It was shown to produce less impact in region 5 than in region 7. This is influenced by climate and feed source. Corn produced in region 5 is generally higher yielding, thus the increased reliance on corn in the LCP ration outweighs the benefits of the cooler climate in region 7. **Error! Reference source not found.** through **Error! Reference source not found.**7 display the national and regional results of the LCP and LCPC ration in each of the four assessment categories.

3.4.3 Process Contribution

Results from Task 2 of this project showed that on average 96% of the land occupation associated with the production of pork prepared for consumption could be attributed to feed rations. The results from the feed scenario comparison were aligned with that finding, showing an average of 96.7% (±2%) land occupation from feed rations across all scenarios. The average feed contribution for water use and carbon footprint was 80.3% (±12%) and 61.4% (±6%), respectively. Figure 3.8 shows the impact contribution from each scenario broken down by unit process. Note that cost is in reference to feed only, not the entire live swine operational costs.

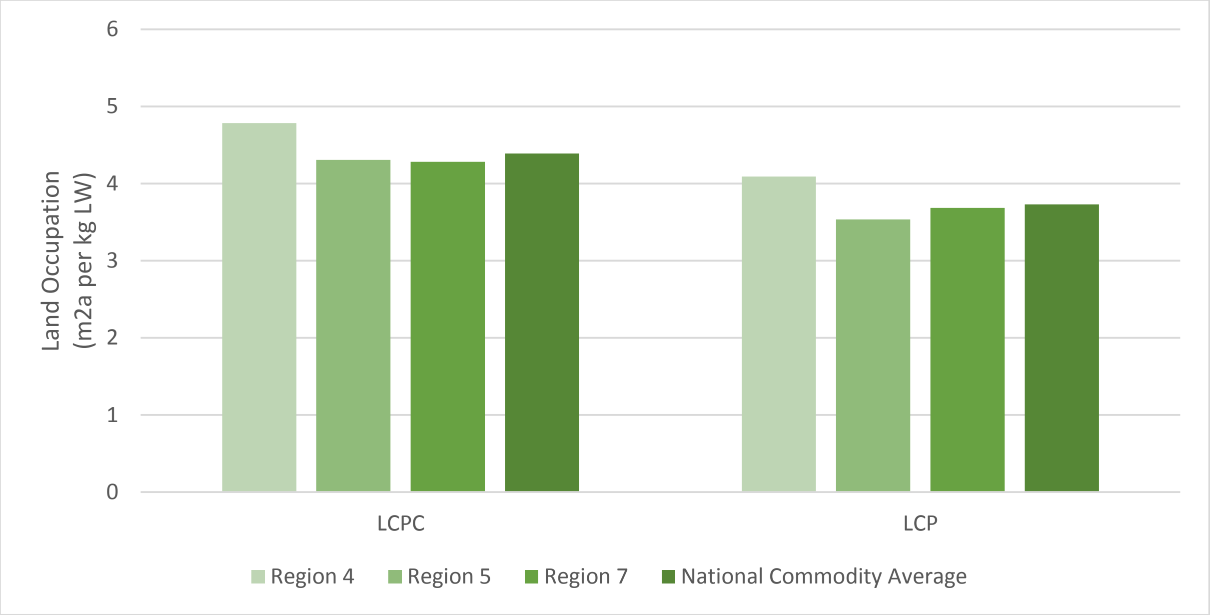

Figure 3.6: Land occupation for each region of production and as a national average using commodity feed

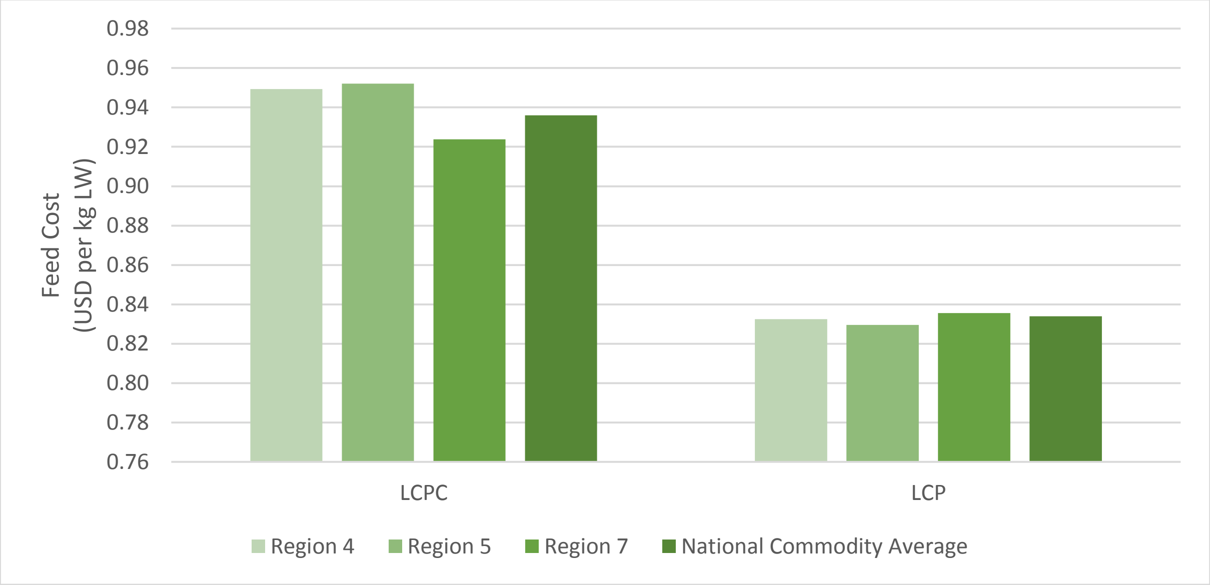

Figure 3.7: Feed cost for each region of production and as a national average using commodity feed

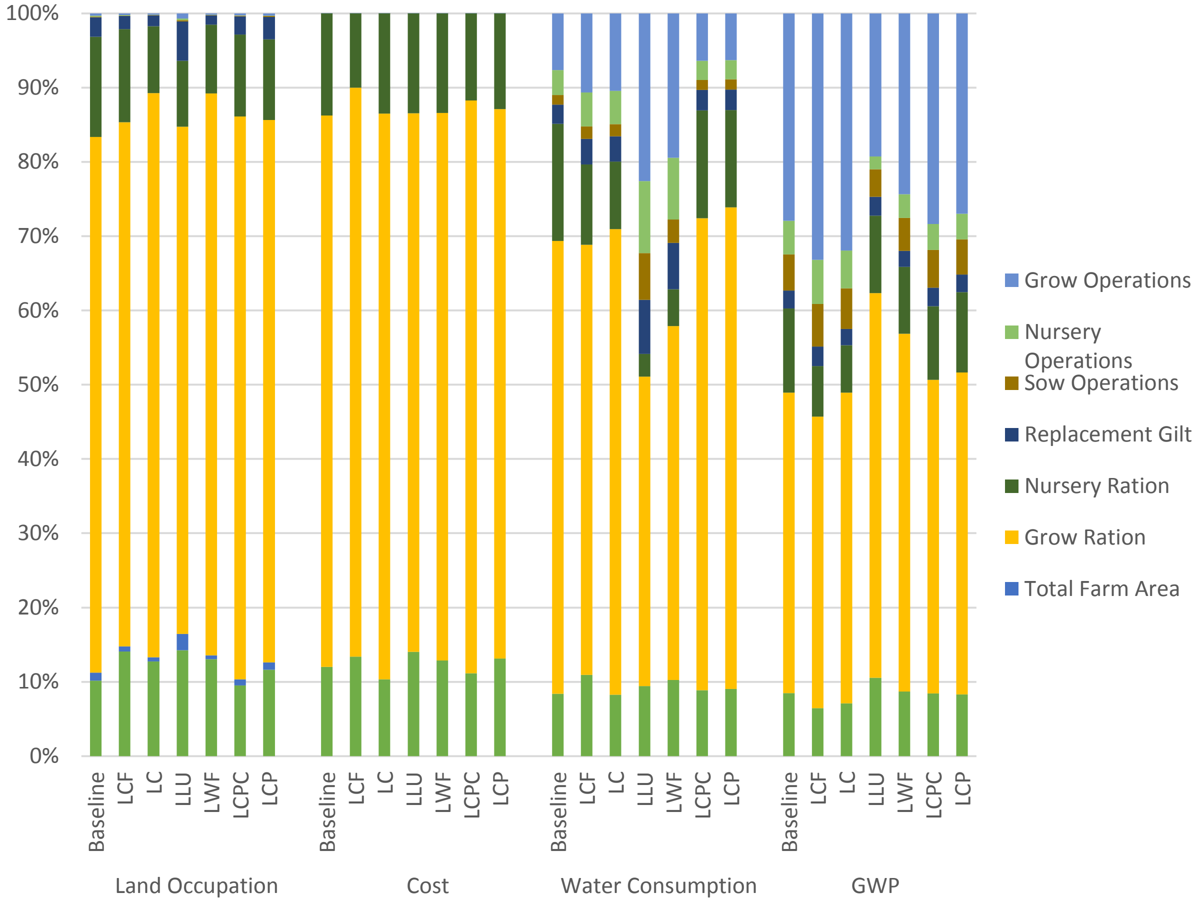

Figure 3.8: Potential impact contribution from each unit process across all scenarios and categories

3.4.4 Uncertainty Analysis

Monte Carlo simulations were performed for the national average pork production in regards to land occupation. The national average was determined by combining the three regions in proportion to the number of head produced in each for the year 2012 according to USDA NASS census data. Results are shown in Figure 3.9. The simulations consisted of 1000 runs for each feed scenario reported using a confidence level of 95%. Uncertainty parameters inherent to unit processes within the background databases were adopted without modification, except in the case of field peas. The unit process for field peas was adopted from the Agri-footprint database, which included a high degree of uncertainty. Yield rates for field peas in the US range from 800 – 2830 lbs/acre, and this high degree of variability was accounted for within the unit process. However, such a wide range of uncertainty resulted in land occupation values ranging from -59 to +128 m^2a/kg LW and was therefore set to a static value of 1603 pounds of field peas per acre.

Results from the uncertainty analysis indicate that the associated land occupation values for each least-cost/footprint ration scenario vary in their ranges of uncertainty. The LLO scenario is associated with the least land occupation, while the LWU scenario maintains the largest associated land occupation, partially attributable to the reliance on non-commodity crops, which are often grown in rotation and on average, tend to be lower yielding crops.

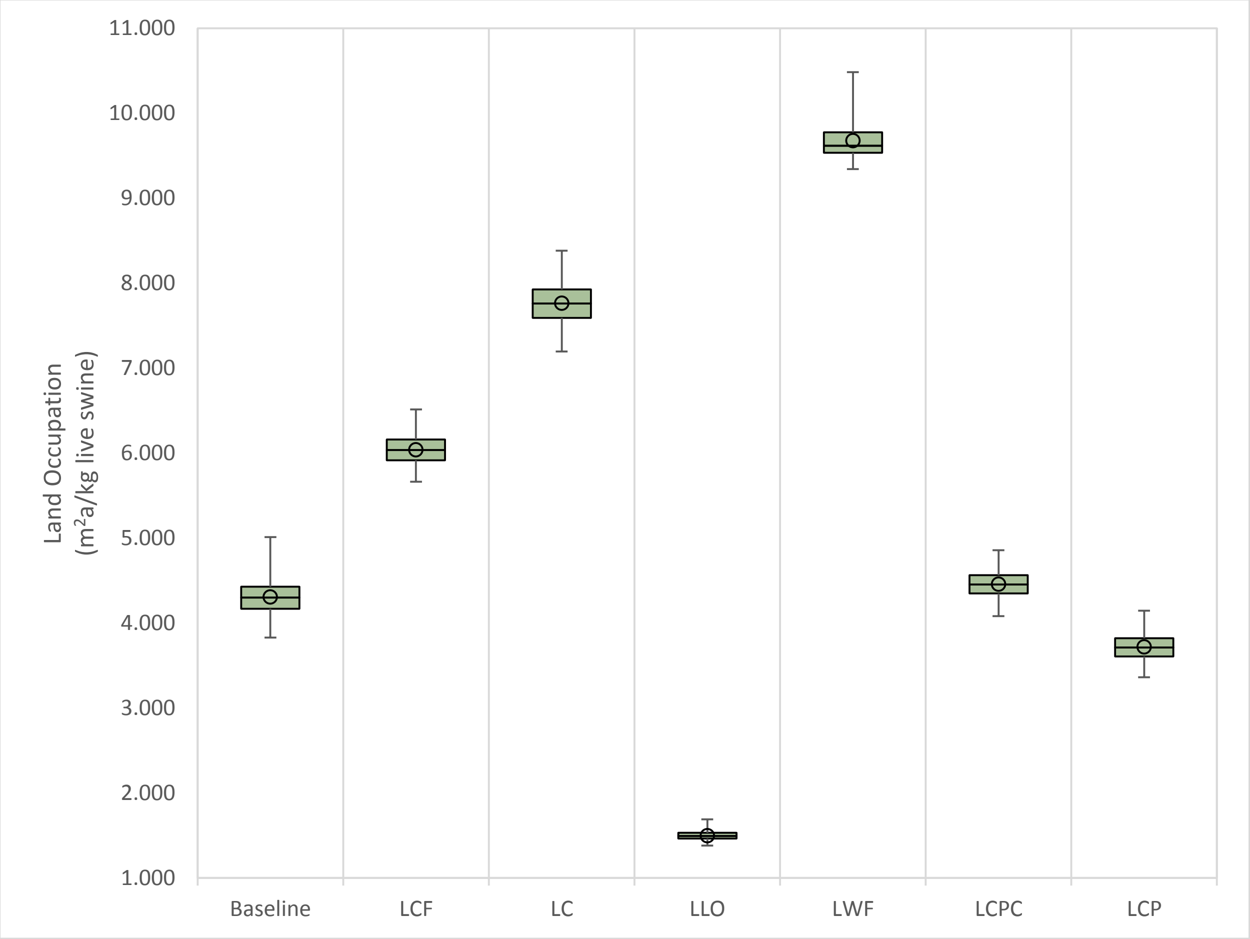

Figure 3.9: Uncertainty analysis of land occupation for all seven feed scenarios. The box represents 25th and 75th percentile of 1000 Monte Carlo runs, the centerline represents the median, the whiskers indicate the minimum and maximum, and the circle represents

3.4.5 Sensitivity Analysis

A sensitivity analysis was conducted to determine to what degree LCA results change in relation to adjusting the model input parameters. Recently, the gestation stall system has faced consumer scrutiny for its perceived limitations to animal mobility (Tonsor et al. 2009). Considering this attitude, an alternative Sow Barn model was created to represent a “semi-natural” husbandry system. It was designed to mimic a family pen system, such as the one used by Arey & Sancha (1996). The system assumed sows were housed in groups of four with voluntary-access farrowing pens attached to a communal area. It is intended to accommodate changing behaviors of sows and their piglets over the course of the gestation and farrowing phases. This production practice would result in a 30% increase in sow barn area over the gestation stall system (Purdue Extension. 2008), contributing a 9% increase in the total land occupied by the swine farm.

The linear regression equation used to model on-farm land occupation assumed no difference between manure management practices. In order to account for the potential variation in land use associated with the different manure management methods, an additional 9% was included in the sensitivity analysis so that the size of the swine farm was analyzed at ±9% and ±18% from the baseline. The results are shown in Table 3.6.

The sensitivity analysis suggests that the average US swine farm contributes only 1.05% of the land occupation required to produce the functional unit. Increasing the swine farm area by 18% only increases the total land occupation by 0.19%. Therefore, we conclude that the land occupation footprint is not likely to be affected by the choice of manure management system. It is important to note that in this LCA the system boundary for manure is cut off at the farm boundary and does not extend to field crops where the manure may be applied. In this accounting scheme, the land occupation associated with crops is included only for crops used in the ration – inclusion of land requirements for spreading manure would result in a potential double counting of land use.

Table 3.6: Results of the sensitivity analysis regarding the effects of on-farm land occupation on the total occupation associated with the production of the functional unit.

Scenario	Swine Farm (m^2)	Change in Footprint	Contribution to Total	Total Footprint (m^2)
Baseline	0.045	0.00%	1.05%	4.305
9% increase	0.049	0.09%	1.14%	4.309
9% decrease	0.041	-0.09%	0.96%	4.301
18% increase	0.053	0.19%	1.24%	4.313
18% decrease	0.037	-0.19%	0.86%	4.297

When modeling methodology can affect the reported results, as in the case of allocation in this work, it is important to determine if the allocation choice affects the robustness of the conclusions. The allocation method used in the LCI stage (associated with feeds that are byproducts, such as distillers grains) of this assessment was identified as a potentially important factor affecting the reported LCA results.

In order to determine the sensitivity of the results to the allocation methodology, economic, mass and energy allocation methods were evaluated for all 7 scenarios. Results are shown in **Error! Reference source not found.**1. Mass allocation refers to the distribution of impacts according to the mass of each coproduct produced from the original product or process. Energy allocation distributes impacts according to the total (gross calorific) energy content of each coproduct. Figure 3.10 displays a flow diagram for economic allocation using soybeans as an example. All allocation values were based on peer-reviewed literature or calculated according to generally accepted standards (Thoma et al., 2011; Blonk Consultants, 2014).

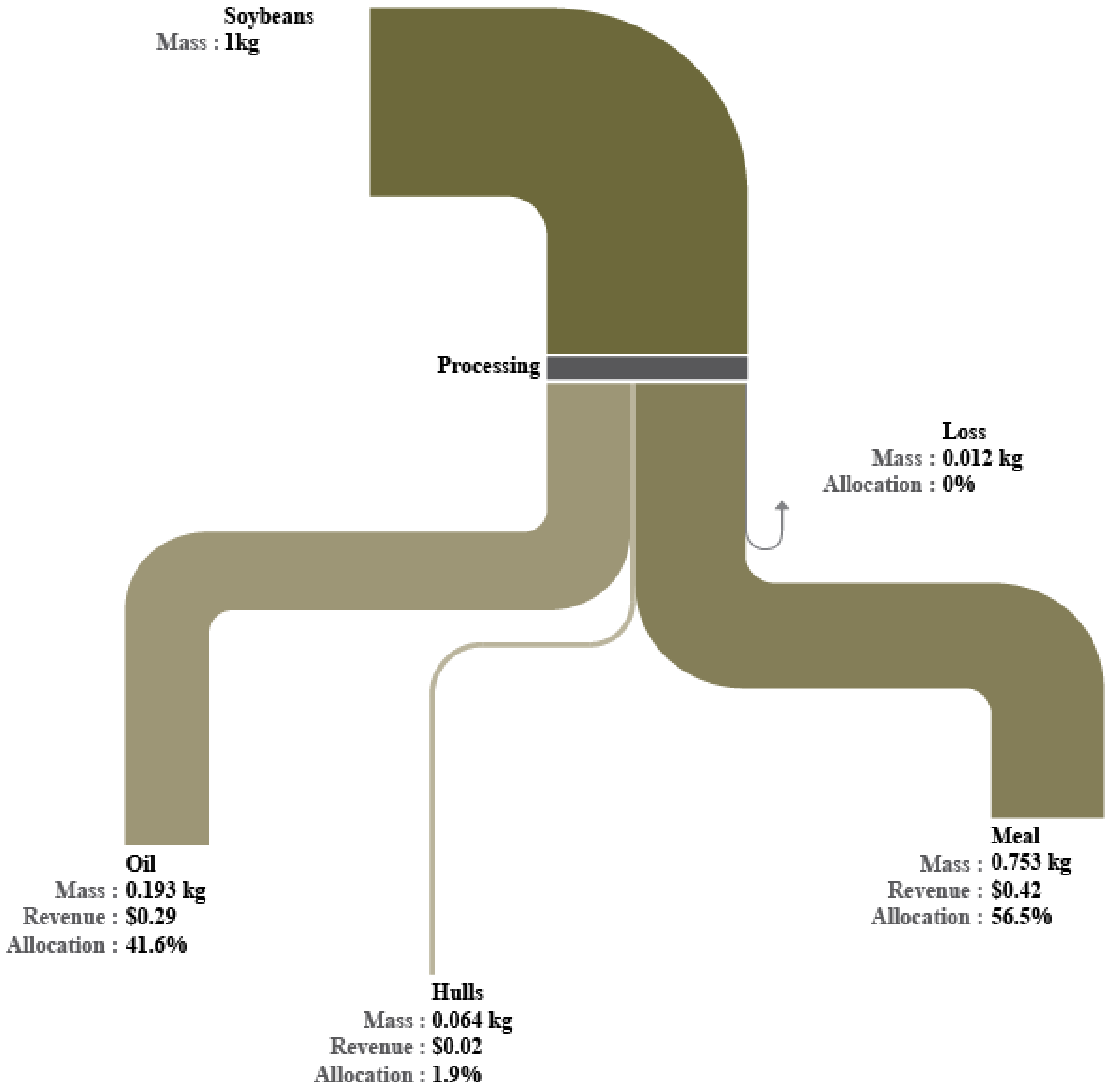

Figure 3.10: Allocating burdens according to their economic value. The revenue values are based on price per kilogram (Burek et al. 2014).

In 93% of cases, the economic allocation of feed byproducts resulted in the least impact to the functional unit. Mass allocation resulted in the greatest impact in 78% of cases. Results from this analysis suggested that the Baseline, Least Crude Protein Control, and Least Crude Protein rations were less sensitive to allocation methods than the least cost/footprint rations. The Baseline, LCPC, and LCP more closely resemble a typical swine ration for the US production, which only contains two or three ingredients with allocated upstream burdens.

The least cost/footprint rations showed greater variation between methods, most notably the Least Land Occupation and Least Water Use rations. The more coproducts included in the ration generally led to increased sensitivity to the allocation method. For example, the Least Land Use scenario ration was composed of 11 coproducts and the land occupation associated with this ration ranged from 2.15 m^2a/kg LW (economic) to 5.12 m^2a/kg LW (mass) [10.5 – 25 ft^2a/lb].

Compare that to the Baseline ration, which had only two coproducts and ranged from 4.21-4.68 m^2a/kg LW [20.5 – 22.8 ft^2a/lb] (economic-mass).

In agricultural lifecycle assessment, economic allocation for the byproducts is the most commonly used approach. As shown in **Error! Reference source not found.**1, there are some differences, which arise from the choice of allocation method, but the overall conclusions of the study are not affected by these differences.

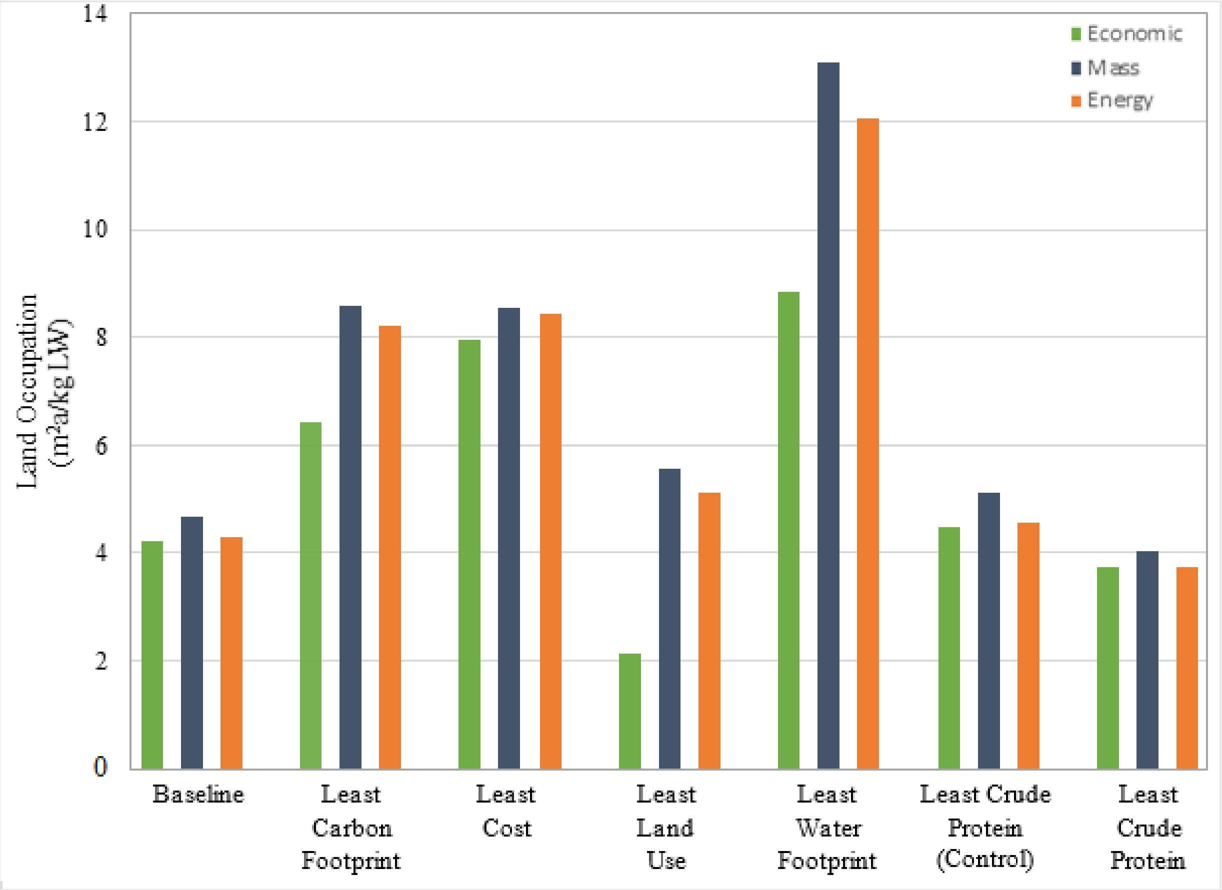

Figure 3.11: Sensitivity results from three different allocation methods on all scenario rations.

3.5 Conclusions

The results of this LCA demonstrate the relative contribution of all inputs to the land occupation attributed to the production of 1kg of live swine in the US Feed rations by far contribute the most, and their effect on land occupation can vary greatly depending on the type of ingredients used. By-products and agricultural derivatives most effectively reduce associated land occupation when allocating burdens according to their economic value. Corn and wheat are the greatest contributors to water use in feed rations. Wheat contributes a much larger land footprint, and much smaller carbon footprint, on a per kilogram basis because it is a lower-yielding crop but also receives less fertilizer than other crops like corn.

When optimizing a ration using the WUFFDA model, doing so for the impact category land occupation (LLO) not only yields the least environmental burden for land, but also demonstrated reduced water use and carbon footprint over the Baseline. The environmental advantages of this ration however resulted in higher feed cost. The LLO was the second most expensive, which highlights the challenge of reducing the global land footprint of agriculture while maintaining profitability.

Sensitivity analysis suggests that the land occupation associated with producing the functional unit is not significantly influenced by the size of the swine farm (exclusive of land the farmer may use for producing the ration). In addition, the least cost/footprint rations were generally more sensitive to the allocation method used - which means that a different choice of allocation methodology would have led to a different formulation for the ration, and that therefore methodological consistency will be critical in developing multi-criteria optimization algorithms.

The LCP ration displayed promise in regards to reducing the feed cost and land occupation. This ration was shown to reduce land occupation by 19% and feed cost by 12%, on average, when compared to the control (LCPC). The tradeoff comes in the form of carbon footprint, for which the LCP ration showed an 8% increase.

A significant conclusion of this work is that, based on available data, the tradeoffs between economic performance and profitability pose challenges to the industry with regard to efforts to use ration manipulation as a means to reduce environmental impacts. Additional work on evaluating weighted multi-criteria approaches may provide better understanding of the opportunities.

References

Amon, B., V. Kryvoruchko, M. Fröhlich, T. Amon, A. Pöllinger, I. Mösenbacher, and A. Hausleitner. 2007. Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: Housing and manure storage. Livest. Sci. 112(3): 199–207Available at http://linkinghub.elsevier.com/retrieve/pii/S1871141307004696 (verified 6 February 2014).

Apple, J., W.S. Yancey, J.J. Hollenbeck, T.M. Johnson, B.E. Bass, T.C. Tsai, C. V. Maxwell, M.D. Hanigan, J.S. Radcliffe, B.T. Richert, J.S. Popp, R. Ulrich, and G. Thoma. 2013. Effects of amino acid supplementation of reduced crude protein (RCP) diets on LM quality of growing-finishing swine. p. 102. In Journal of Animal Science.

Arey, D.S., Sancha, E.S., 1996. Behaviour and Productivity of Pigs in a Semi-Natural Environment. Animal Production. 1989(48):419-425.

Basarab, J., V. Baron, Ó. López-Campos, J. Aalhus, K. Haugen-Kozyra, and E. Okine. 2012. Greenhouse Gas Emissions from Calf- and Yearling-Fed Beef Production Systems, With and Without the Use of Growth Promotants. Animals 2(4): 195–220Available at http://www.mdpi.com/2076-2615/2/2/195/ (verified 17 July 2014).

Basset-mens, C., and H.M.G. van der Werf. 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. Agric. Ecosyst. Environ. 105(1-2): 127–144Available at http://linkinghub.elsevier.com/retrieve/pii/S0167880904001744 (verified 9 September 2010).

Beck, T., U. Bos, B. Wittstock, M. Baitz, M. Fischer, and K. Sedlbauer. 2011. Land Use Indicator Value Calculation in Life Cycle Assessment – Method Report. Fraunhofer Verlag.

Blonk Consultants. 2014. Agri-footprint database. Available at: http://www.agri-footprint.com/

Blonk H, Kool A, Luske B, de Waarf S (2008) Environmental effects of protein-rich food products in the Netherlands Consequences of animal protein substitutes. 1–19.

Boyd, G., and R. Cady. 2012. A 50-Year Comparison of the Carbon Footprint and Resource Use of the US Swine Herd : 1959 - 2009.

Brandão, M., and L.M. Canals. 2012. Global characterisation factors to assess land use impacts on biotic production. Int. J. Life Cycle Assess. 18(6): 1243–1252Available at http://link.springer.com/10.1007/s11367-012-0381-3 (verified 14 July 2014).

British Standards Institution. 2011. Publically Available Specification 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. PAS 2050:2. BSI.

Burek, J., G. Thoma, J. Popp, C. V. Maxwell, and R. Ulrich. 2014. Developing Environmental Footprint , Cost , and Nutrient Database of the US Animal Feed Ingredients. p. 1–9. In Ninth International Life Cycle Assessment of Foods Conference.

Castellini, C., A. Boggia, L. Paolotti, G.J. Thoma, and D. Kim. 2012. Environmental Impacts and Life Cycle Analysis of Organic Meat Production and Processing. In S. C. Ricke, Loo, E.J. Van, Johnson, M.G., O'Bryan, C.A. (eds.), Organic Meat Production and Processing. S. C. Ricke, E. J. Van Loo, M. G. Johnson and C. A. O'Bryan, Oxford, UK.

Cederberg, C., and A. Flysjö. 2004. Environmental assessment of future pig farming systems–quantification of three scenarios from the FOOD 21 synthesis work. Swedish Institute for Food and Biotechnology.

Cederberg, C., U. Sonesson, M. Henriksson, V. Sund, and J. Davis. 2009. Greenhouse gas emissions from Swedish production of meat, milk and eggs 1990 and 2005. Gothenberg, SE.

Dalgaard, R.L. 2007. The environmental impact of pork production from a life cycle perspective. : 143.

Dalgaard, R.L., N. Halberg, and J.E. Hermansen. 2007. Danish pork production: an environmental assessment.

De Baan, L., C.L. Mutel, M. Curran, S. Hellweg, and T. Koellner. 2013. Land use in life cycle assessment: global characterization factors based on regional and global potential species extinction. Environ. Sci. Technol. 47(16): 9281–90.

De Vries, M., and I.J.M. de Boer. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. Livest. Sci. 128(1-3): 1–11Available at http://linkinghub.elsevier.com/retrieve/pii/S1871141309003692 (verified 7 August 2013).

Dong, H., Z. Zhu, B. Shang, G. Kang, H. Zhu, and H. Xin. 2007a. Emissions of greenhouse gases from a typical Chinese swine farrowing barn. Trans. ASABE 50(3): 1037–1044Available at http://lib.dr.iastate.edu/abe_eng_pubs/171/ (verified 18 December 2013).

Dong, H., Z. Zhu, B. Shang, G. Kang, H. Zhu, and H. Xin. 2007b. Greenhouse gas emissions from swine barns of various production stages in suburban Beijing, China. Atmos. Environ. 41(11): 2391–2399Available at http://linkinghub.elsevier.com/retrieve/pii/S1352231006011101 (verified 24 July 2014).

Dong, H., Z. Zhu, Y. Li, X. Tao, and H. Xin. 2005. Temporal Variation of Greenhouse Gas Emission in Gestation Swine Building. In Livestock Environment VII.

EarthShift. 2011. US-EI v.2.2 LCI database. Available at http://www.earthshift.com/software/simapro/USEI-database.

Foley, J. a, N. Ramankutty, K. a Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman, and D.P.M. Zaks. 2011. Solutions for a cultivated planet. Nature 478(7369): 337–42Available at http://www.ncbi.nlm.nih.gov/pubmed/21993620 (verified 9 July 2014).

Food and Agriculture Organization of the United Nations. 2013. FAO Statistical Yearbook 2013. Rome.

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, R. Van Dorland, D. Qin, M. Manning, Z. Chen, M. Marquis, and K.B. Averyt. 2007. Changes in Atmospheric Constituents and in Radiative Forcing. In Solomon, S.D., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (eds.), Climate Change 2007: The Physical Science Basis. Contributi. Cambridge University Press, Cambridge, United Kingdom and New York, NY, US.

Frischknecht, R., N. Jungbluth, H. Althaus, C. Bauer, G. Doka, R. Dones, R. Hischier, S. Hellweg, S. Humbert, T. Köllner, and others. 2007. Implementation of life cycle impact assessment methods.

Fry, J., and C. Kingston. 2009. Life Cycle Assessment of Pork.

Garcia-Launay, F., H.M.G. van der Werf, T.L.T. Nguyen, L. Le Tutour, and J.Y. Dourmad. 2014. Evaluation of the environmental implications of the incorporation of feed-use amino acids in pig production using Life Cycle Assessment. Livest. Sci. 161: 158–175Available at http://linkinghub.elsevier.com/retrieve/pii/S1871141313005209 (verified 13 May 2014).

Gonyou, H.W., M.C. Brumm, E. Bush, J. Deen, S.A. Edwards, T. Fangman, R.B. Morrison, H. Spoolder, P.L. Sundberg, and J.J. Mcglone. 2014. Application of broken-line analysis to assess floor space requirements of nursery and grower-finisher pigs expressed on an allometric basis The online version of this article , along with updated information and services , is located on the World Wide Web. : 229–235.

Halberg, N., J.E. Hermansen, I.S. Kristensen, J. Eriksen, and N. Tvedegaard. 2008. Comparative environmental assessment of three systems for organic pig production in Denmark. p. 249–261. In Köpke, U., Sohn, S.M. (eds.), ISOFAR Conference Series.

Koellner, T., and R. Geyer. 2013. Global land use impact assessment on biodiversity and ecosystem services in LCA. Int. J. Life Cycle Assess. 18(6): 1185–1187Available at http://link.springer.com/10.1007/s11367-013-0580-6 (verified 15 July 2014).

Koellner, T., L. Baan, T. Beck, M. Brandão, B. Civit, M. Margni, L.M. Canals, R. Saad, D.M. Souza, and R. Müller-Wenk. 2013. UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. Int. J. Life Cycle

Assess. 18(6): 1188–1202Available at http://link.springer.com/10.1007/s11367-013-0579-z (verified 23 February 2014).

Lammers, P J., M. S. Honeyman, J. D. Harmon, J. B. Kliebenstein, M. J. Helmers. 2009. Construction Resource Use of Two Different Types and Scales of Iowa Swine Production Facilities. Applied Engineering in Agriculture. 24(4): 585-594

Lammers, P.J., M.S. Honeyman, J.D. Harmon, and M.J. Helmers. 2010. Energy and carbon inventory of Iowa swine production facilities. Agric. Syst. 103(8): 551–561Available at http://linkinghub.elsevier.com/retrieve/pii/S0308521X10000788 (verified 11 May 2014).

Lawrence, J., and G. Grimes. 2007. Production and marketing characteristics of US pork producers, 2006. Department of Agricultural Economics Working Paper; No. AEWP 2007-05.

Lindeijer, E. 2000. Biodiversity and life support impacts of land use in LCA. J. Clean. Prod. 8(4): 313–319Available at http://linkinghub.elsevier.com/retrieve/pii/S0959652600000251 (verified 18 July 2014).

Macleod, M., P. Gerber, A. Mottet, G. Tempio, A. Falucci, C. Opio, T. Vellinga, B. Henderson, and H. Steinfield. 2013. Greenhouse gas emissions from pig and chicken supply chains - A global life cycle assessment. Food and Agriculture Organization of the United Nations, Rome, IT.

Matlock M, Thoma G, Boles E, et al. (2014) A Life Cycle Analysis of Water Use in Swine Production, Comprehensive Report to the National Pork Board. Fayetteville, AR

Thoma G, M. Matlock, P. Bandekar. (2013) LCA of Alternate Swine Management Practices, Report to the National Pork Board. Fayetteville, AR

Maxwell, C. V., J.K. Apple, S. Radcliffe, and B. Richert. 2012. The Effects of Amino Acid Supplementation with Reduced Dietary Crude Protein on Nursery Performance.

Mcglone, J., S. Ford, F. Mitloehner, T. Grandin, P. Ruegg, J. Swanson, W. Underwood, S. Eicher, P. Hester, J. Salak-johnson, S. Ford, M. Bailey, S. Berry, and L. Hollis. 2010. Guide for the Care and Use of Agricultural Animals in Research and Teaching.

McGlone, J.J. and B. E. Newby. 1994. Space requirements for finishing pigs in confinement: behavior and performance while group size and space may vary. Appl. Anim. Sci. 39:331-338

Meul, M., C. Ginneberge, C.E. Van Middelaar, I.J.M. de Boer, D. Fremaut, and G. Haesaert. 2012. Carbon footprint of five pig diets using three land use change accounting methods. Livest. Sci. 149(3): 215–223 Available at http://linkinghub.elsevier.com/retrieve/pii/S1871141312002752 (verified 11 November 2013).

Milà i Canals, L., C. Bauer, J. Depestele, A. Dubreuil, and R.F. Knuchel. 2007. Key Elements in a Framework for Land Use Impact Assessment within LCA Land Use in LCA. Int. J. Life Cycle Assess. 12(1): 5–15.

Milà i Canals, L., G. Rigarlsford, and S. Sim. 2012. Land use impact assessment of margarine. Int. J. Life Cycle Assess. 18(6): 1265–1277Available at http://link.springer.com/10.1007/s11367-012-0380-4 (verified 18 July 2014).

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, DC.

Mosnier, E., H.M.G. van der Werf, J. Boissy, and J.Y. Dourmad. 2011. Evaluation of the environmental implications of the incorporation of feed-use amino acids in the manufacturing of pig and broiler feeds using Life Cycle Assessment. Animal 5(12): 1972–83Available at http://www.ncbi.nlm.nih.gov/pubmed/22440474 (verified 26 July 2014).

Müller-Wenk, R., and M. Brandão. 2010. Climatic impact of land use in LCA—carbon transfers between vegetation/soil and air. Int. J. Life Cycle Assess. 15(2): 172–182Available at http://link.springer.com/10.1007/s11367-009-0144-y (verified 11 July 2014).

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhan. 2013. Anthropogenic and Natural Radiative Forcing. p. 659–740. In Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, United Kingdom and New York, NY, USA.

National Pork Board. 2015. Carbon Footprint of Pork Production Calculator - Pork Checkoff.

National Research Council. 2012. Nutrient Requirements of Swine: Eleventh Revised Edition. The National Academies Press, Washington, D.C.

Nelson, E., G. Mendoza, J. Regetz, S. Polasky, H. Tallis, Dr. Cameron, K.M. Chan, G.C. Daily, J. Goldstein, P.M. Kareiva, E. Lonsdorf, R. Naidoo, T.H. Ricketts, and Mr. Shaw. 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. Front. Ecol. Environ. 7(1): 4–11Available at http://www.esajournals.org/doi/abs/10.1890/080023 (verified 11 July 2014).

Nguyen, T.L.T., J.E. Hermansen, and L. Mogensen. 2012. Environmental costs of meat production: the case of typical EU pork production. J. Clean. Prod. 28: 168–176Available at http://linkinghub.elsevier.com/retrieve/pii/S0959652611003180 (verified 3 June 2014).

Ni, J.-Q., A.J. Heber, T.T. Lim, P.C. Tao, and A.M. Schmidt. 2007. Methane and carbon dioxide emission from two pig finishing barns. J. Environ. Qual. 37(6): 2001–11Available at http://www.ncbi.nlm.nih.gov/pubmed/18948452.

Nijdam, D., T. Rood, and H. Westhoek. 2012. The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy 37(6): 760–770Available at http://linkinghub.elsevier.com/retrieve/pii/S0306919212000942 (verified 11 November 2013).

Ogino, A., T. Osada, R. Takada, T. Takagi, S. Tsujimoto, T. Tonoue, D. Matsui, M. Katsumata, T. Yamashita, and Y. Tanaka. 2013. Life cycle assessment of Japanese pig farming using low-protein diet supplemented with amino acids. Soil Sci. Plant Nutr. 59(1): 107–118Available at http://www.tandfonline.com/doi/abs/10.1080/00380768.2012.730476 (verified 26 July 2014).

Olea Perez, R., J. GUY, H. EDGE, E.A. STOCKDALE, and S.A. EDWARDS. 2009. Pigmeat supply chain: Life Cycle Analysis of contrasting pig farming scenarios. p. 91. In Aspects of Applied Biology 95, Measuring and marketing the environments costs and benefits of agricultural practice. ASSOCIATION OF APPLIED BIOLOGISTS.

Pelletier, F., S. Godbout, S.P. Lemay, R.D. von Bernuth, S. Pigeon, and J.Y. Drolet. 2007. Evaluation of Greenhouse Gas Emissions from Five Swine Production Systems Based on Life Cycle Assessment. In 2007 ASABE Annual International Meeting. American Society of Agricultural and Biological Engineers.

Pelletier, N., P.J. Lammers, D. Stender, and R. Pirog. 2010. Life cycle assessment of high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States. Agric. Syst. 103(9): 599–608Available at http://linkinghub.elsevier.com/retrieve/pii/S0308521X10000922 (verified 30 April 2014).

Pesti, G., E. Thomson, R. Bakalli, B. Leclercq, A. Shan, A. Atencio, J. Driver, C. Zier, M. Azain, M. Pavlak, D. Vedenov, F. van de Vyver, Jose Fernando Menten, J.O. Sorbara, N. Senkoylu, M. Chamruspollert, and R.K. Seon. 2008. Windows User-Friendly Feed Formulation.

PRé Consultants. 2014. SimaPro 8.3. Available at http://www.pre-sustainability.com/.

Richert, B.T., and J. DeRouchey. 2007. Swine Feed Processing and Manufacturing.

Saad, R., T. Koellner, and M. Margni. 2013. Land use impacts on freshwater regulation, erosion regulation, and water purification: a spatial approach for a global scale level. Int. J. Life Cycle Assess. 18(6): 1253–1264Available at http://link.springer.com/10.1007/s11367-013-0577-1 (verified 18 July 2014).

Scherer, T., F. Franzen, D. Cihacek, L. 2013. Soil, Water and Plant Characteristics Important to Irrigation. North Dakota State University Extension Service.

Souza, D.M., D.F.B. Flynn, F. DeClerck, R.K. Rosenbaum, H. Melo Lisboa, and T. Koellner. 2013. Land use impacts on biodiversity in LCA: proposal of characterization factors based on functional diversity. Int. J. Life Cycle Assess. 18(6): 1231–1242Available at http://link.springer.com/10.1007/s11367-013-0578-0 (verified 18 July 2014).

Stein, H.H., and G.C. Shurson. 2009. Board-invited review: the use and application of distillers dried grains with solubles in swine diets. J. Anim. Sci. 87(4): 1292–303Available at http://www.ncbi.nlm.nih.gov/pubmed/19028847 (verified 17 November 2010).

Stone, J.J., C.R. Dollarhide, J.L. Benning, C. Gregg Carlson, and D.E. Clay. 2012. The life cycle impacts of feed for modern grow-finish Northern Great Plains US swine production. Agric. Syst. 106(1): 1–10Available at http://linkinghub.elsevier.com/retrieve/pii/S0308521X11001533 (verified 11 November 2013).

Stone, J.J., C.R. Dollarhide, R. Jinka, R.C. Thaler, C.E. Hostetler, and D.E. Clay. 2010. Life Cycle Assessment of a Modern Northern Great Plains US Swine Production Facility. Environ. Eng. Sci. 27(12): 1009–1018Available at http://www.liebertonline.com/doi/abs/10.1089/ees.2010.0051 (verified 18 July 2014).

Strid Eriksson, I., H. Elmquist, S. Stern, and T. Nybrant. 2004. Environmental Systems Analysis of Pig Production - The Impact of Feed Choice. Int. J. Life Cycle Assess. 10(2): 143–154Available at http://www.springerlink.com/index/10.1065/lca2004.06.160 (verified 18 December 2013).

Tallis, H., and S. Polasky. 2009. Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. Ann. N. Y. Acad. Sci. 1162: 265–83Available at http://www.ncbi.nlm.nih.gov/pubmed/19432652 (verified 10 July 2014).

Thoma, G.J., D. Nutter, R. Ulrich, C. Maxwell, J. Frank, and C. East. 2011. National life cycle carbon footprint study for production of US swine. National Pork Board, Des Moines, IA. Des Moines, IA.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108(50): 20260–4Available at http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3250154&tool=pmcentrez&rendertype=abstract (verified 19 March 2014).

Tonsor, G.T., N. Olynk, C. Wolf. 2009. Consumer Preferences for Animal Welfare Attributes: The Case of Gestation Crates. Journal of Agricultural and Applied Economics. 41(3): 713-730.

US Pork Center of Excellence. 2010. National swine nutrition guide (D Meisinger, Ed.). Des Moines, IA.

Van der Werf, H.M.G., J. Petit, and J. Sanders. 2005. The environmental impacts of the production of concentrated feed: the case of pig feed in Bretagne. Agric. Syst. 83(2): 153–177Available at http://linkinghub.elsevier.com/retrieve/pii/S0308521X04000587 (verified 18 July 2014).

Vergé, X.P.C., J.A. Dyer, R.L. Desjardins, and D. Worth. 2008. Greenhouse gas emissions from the Canadian pork industry. Agric. Syst. 121(1): 92–101Available at http://linkinghub.elsevier.com/retrieve/pii/S0308521X08000590 (verified 5 September 2010).

Weidema, B.P., C. Bauer, R. Hischier, C.L. Mutel, Nemecek, Thomas, R. J, C.O. Vadenbo, and G. Wernet. 2013. Overview and methodology Data quality guideline for the ecoinvent database version 3. 3(1).

Weiss, F., and A. Leip. 2012. Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. Agric. Ecosyst. Environ. 149: 124–134Available at http://linkinghub.elsevier.com/retrieve/pii/S0167880911004415 (verified 18 July 2014).

Wiedemann, S., E.J. McGahan, S. Grist, and T. Grant. 2010. Environmental Assessment of Two Pork Supply Chains Using Life Cycle Assessment.

Williams, A.G., E. Audsley, and D. Sandars. 2006. Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities.

Zhu, X., and E. van Ierland. 2004. Protein chains and environmental pressures: a comparison of pork and novel protein foods. Environ. Sci. 1(3): 254–276Available at http://www.tandfonline.com/doi/abs/10.1080/15693430412331291652 (verified 24 July 2014).