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A Cradle to Farm Gate Life Cycle Analysis of Land Use in U.S. Pork Production

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ABSTRACT

The goal of this study was to conduct a detailed Life Cycle Assessment (LCA) of the U.S. live swine production supply chain to quantify land use requirements and to assess the impact associated with various ration compositions. 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 U.S. market hog production.

First, a literature review was conducted 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 the detailed LCA.

The study showed that the average land occupation required to produce 1 kg of live swine weight (LW) in the U.S. was 4.22 m^2a. This result is based on a feed ration that was intended to represent a typical U.S. 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 4.59 m^2a/kg LW, followed by 4.13 m^2a/kg LW in Region 5 and 4.11 m^2a/kg LW in Region 7.

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 construct four ration manipulation strategies intended to lower cost, carbon footprint, water use, and land use. Two more rations

were included to assess the increased use of synthetic amino acids. All scenario diets showed impact 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 categories.

ACKNOWLEDGMENTS

My success so far in life would not have been possible without the support of my family, especially my mother and father, who continue to believe in my abilities and be patient with my shortcomings. I am incredibly grateful to Dr. Marty Matlock for giving me the opportunity to participate in this project. Without his assistance, or the guidance of Drs. Greg Thoma and Rusty Bautista, I would not have been successful. I would like also like to recognize the National Pork Board, whose interest in environmental stewardship made this project a possibility.

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INTRODUCTION

Global growth and development coupled with pressures arising from a growing global middle class consuming more animal protein in their diet place 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. 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 U.S. is one of the world's leading pork producers, second only to China. In 2012, the U.S. swine industry accumulated sales of $22.5 billion, representing 6% of all agriculture sales in the U.S. 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 U.S. pigs in inventory averaging 65 million at any given time over the past five years (NASS, 2015), the land use associated with corn grown for pigs is significant.

Life Cycle Assessment (LCA) is a comprehensive methodology for quantitatively analyzing potential impacts and risks associated with complex systems. 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.

Using LCA, this study investigated hotspots in the supply chain where land use was least efficient and expanded the available knowledge regarding the occupation of land throughout the US pork production supply chain. Similar assessments have been conducted for international systems (Zhu and van Ierland, 2004; Dalgaard et al., 2007; Dalgaard, 2007; Fry and Kingston, 2009; Wiedemann et al., 2010; Nguyen et al., 2012) and region-specific U.S. systems (Pelletier et al., 2010; Stone et al., 2012). However, no study had been conducted that addressed land use in pork production on a national level for the U.S.

1. PROBLEM DEFINITION

Objectives

The goal of this study was to quantify land occupation resulting from pork produced and consumed in the U.S. at a national scale. Analyses cover three geographical regions, representing 86% of pork production in the US and covering land uses from cradle to farm gate. The principal focus of this project is land use, but also includes an assessment of trade-offs, which may arise when producers use ration manipulation as a mitigation option.

Hypotheses

H(0)1: All nutritionally-equivalent swine feed rations have approximately the same land footprint.

H(A)1: Some nutritionally-equivalent swine feed rations have a larger footprint than others.

H(0)2: Methods for allocating environmental impact have no effect on land footprint.

H(A)2: Land footprints are affected by allocation methods.

H(0)3: All regions of swine production have approximately the same land footprint.

H(A)3: Land footprints vary with the region of production.

2. LITERATURE REVIEW

Overview of Land Use in Swine Production

The purpose of this literature review is to summarize the most current information and knowledge regarding the status of accounting for land use in agriculture and livestock production. Efforts have been identified that were conducted by other researchers and organizations, nationally and internationally, in order to guide the methods and approaches for a land use footprint for U.S. pork production.

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., 2007). 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, 2011).

Swine Production by Region

The majority of published pork production LCAs come from universities and consultants in the European Union (Zhu and van Ierland, 2004; Dalgaard, 2007; Dalgaard et al., 2007; Fry and Kingston, 2009; Nguyen et al., 2012). Few LCAs have been completed for pork production in the U.S. 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 (Dalgaard, 2007; Ni et al., 2007; Pelletier et al., 2007; Amon et al., 2007; Vergé et al., 2008; Wiedemann et al., 2010; Lammers et al., 2010; Castellini et al., 2012; Weiss and Leip, 2012; Macleod et al., 2013). 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.

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^2/kg live weight (LW) produced (SNC-Lavalin Agro, 2009), which is higher than most other reports. Pelletier et al. (2010) reported ecological footprints between 14.2 and 24 m^2 per kg LW for pigs produced with different practices in the U.S. 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 for cropland) and GHG emissions (2.67 gha/kg CO_2) (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 the land occupation has been estimated based on the literature values for characterization factors (Frischknecht et al., 2007). Based on Pelltier et al. (2010) reported GHG emissions and ecological footprint, land occupation inventory of all relevant processes from cradle to farm gate for this study ranges from 3.5 to7.2 m^2/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.

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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

Stone et. al. (2012) report 147 m^2/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^2/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^2/kg LW) in 2009 based on estimated ration consumption and crop yield. Their study did not include other land occupation within the supply chain.

European Union

The U.S. results aligned with six LCAs on pork production in the EU that addressed land use (Figure 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 m2/kg LW for swine compared to 9.8 to 16.5 m2/kg LW for beef and 4 to 5.5 m2/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.

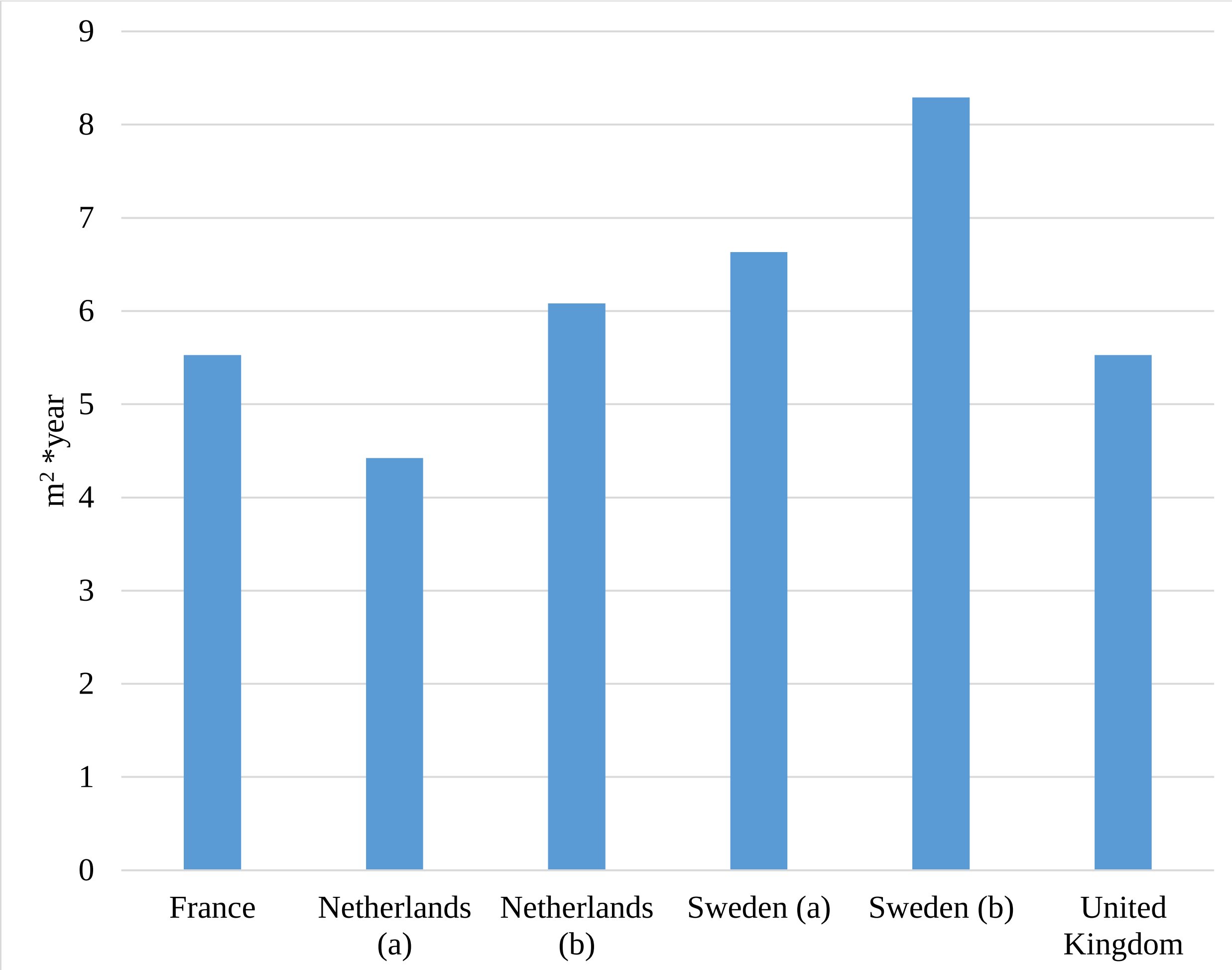

Figure 1: Land use per kilogram live weight at the farm gate meat from six international land use LCAs (France: Basset-Mens & vander Werf 2005; Netherlands (a): Blonk et al 2008; Netherlands (b): Zhu-XueQin & van Ierland 2004; Sweden (a): Cederberg & Flysjo 2004b; Sweden (b): Strid Eriksson et al 2005; United Kingdom: Williams et al 2006)

The European studies provide useful insights for performing an LCA of U.S. pork production, although care must be taken when drawing conclusions from their findings. Figure 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 U.S. and elsewhere. For example, Stone et al. (2010) outlines five important distinctions between EU and U.S. production:

1. Different genetic make-up of EU swine herd

2. Utilization of nontraditional (from a U.S. 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

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.

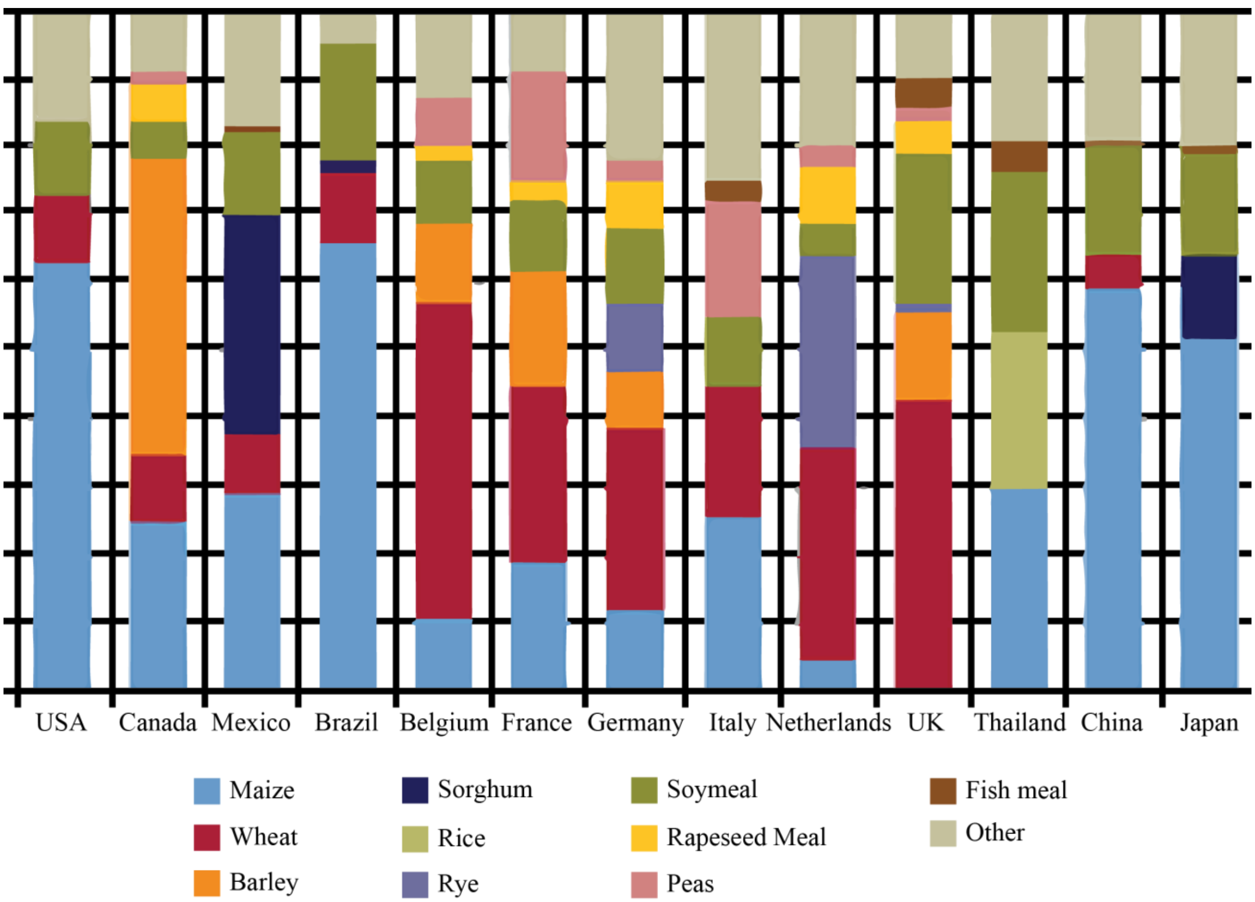

Figure 2: Average swine feed composition in various countries (FAO, 2013).

Other Regions/Studies

Several LCAs conducted outside of the EU and U.S. 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., 2005, 2007a; b). 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 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 U.S. 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 3 displays some of the results.

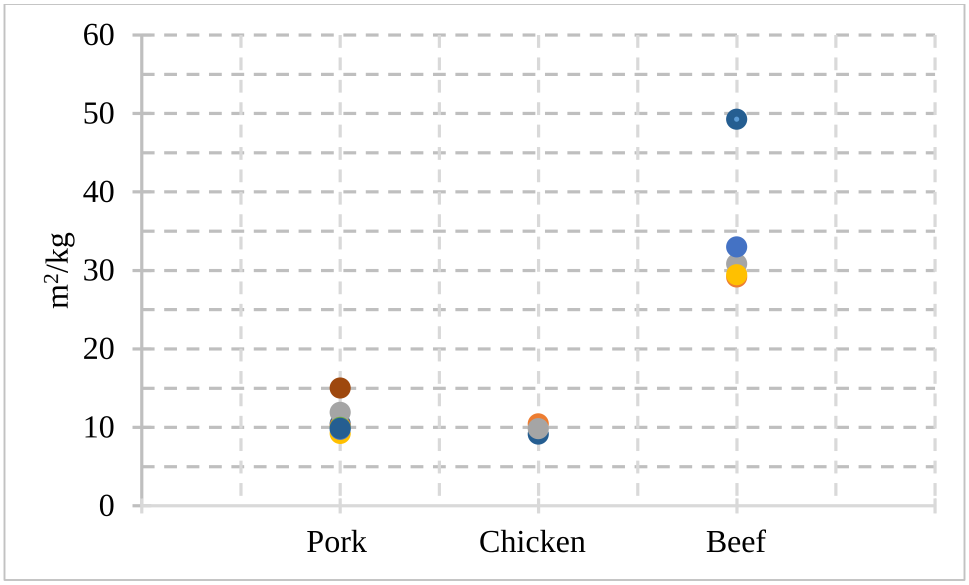

Figure 3: Land use footprint EU livestock products in kg of edible meat (as compiled by de Vries and de Boer 2010)

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.

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., 2005; 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.

Methodological Approaches

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 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 meters squared 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.

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 m2/kg LW or approximately 8.8 m2/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.

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, 2004) 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 follows the previous work and also adopts economic allocation beyond the farm gate.

Production methods

Several studies compared conventional to organic pork production and found significant increases in land use for organic production (Basset-mens and van der Werf, 2005; Williams et al., 2006; Halberg et al., 2008). Halberg et al. reported values ranging from 6.9 to 9.2 m2/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).

Inventory Requirements

This section provides context regarding land use for the live swine production phase of the U.S. 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. Land use input requirements and system boundaries for common levels of analysis are presented in Figure 4.

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).

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 U.S. 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 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 configurations. 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., 2011) and is commonly added in swine rations therefore was considered in this study to evaluate potential effects on land use.

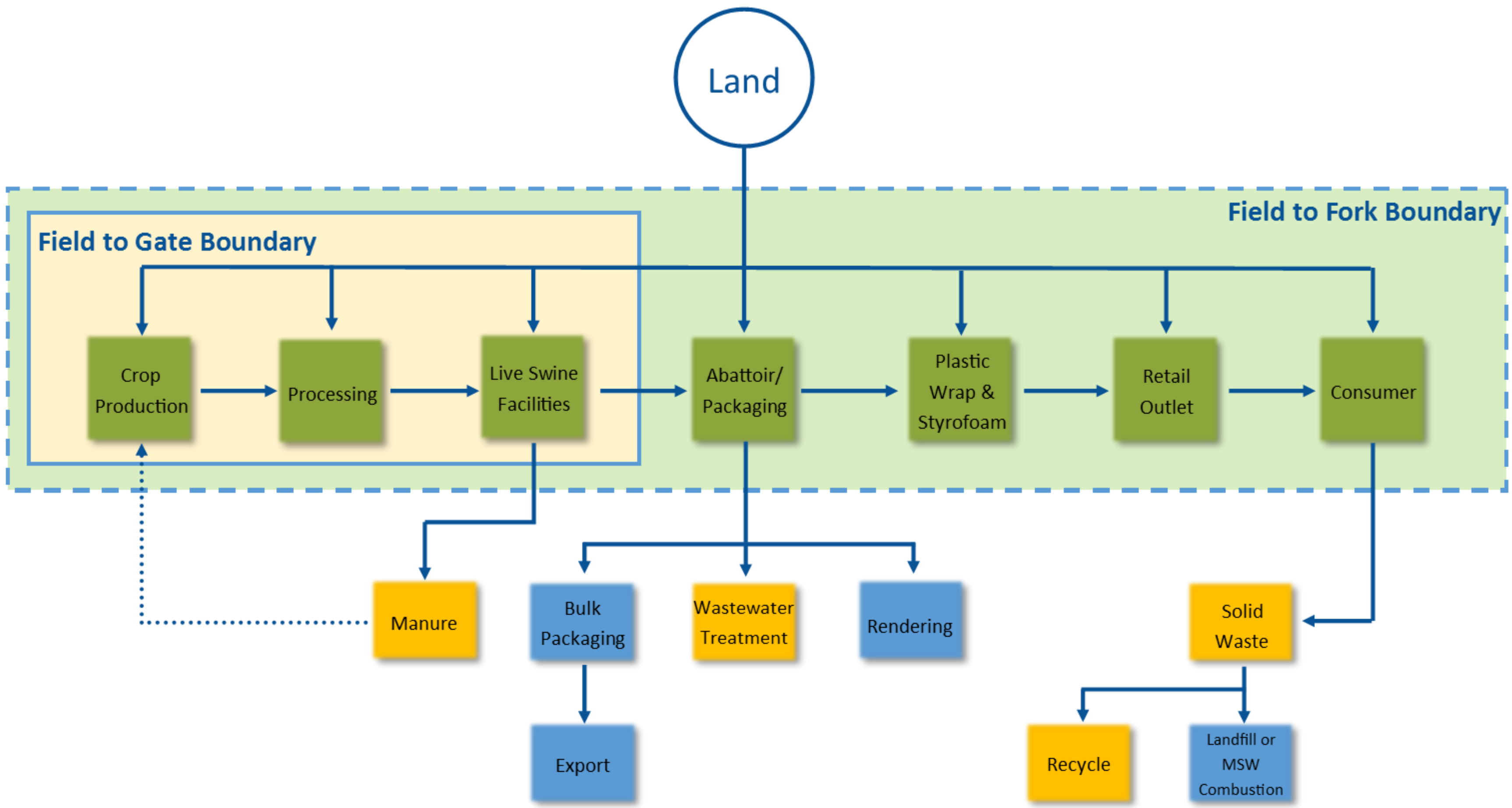

Figure 4: System boundaries for pork land use LCAs

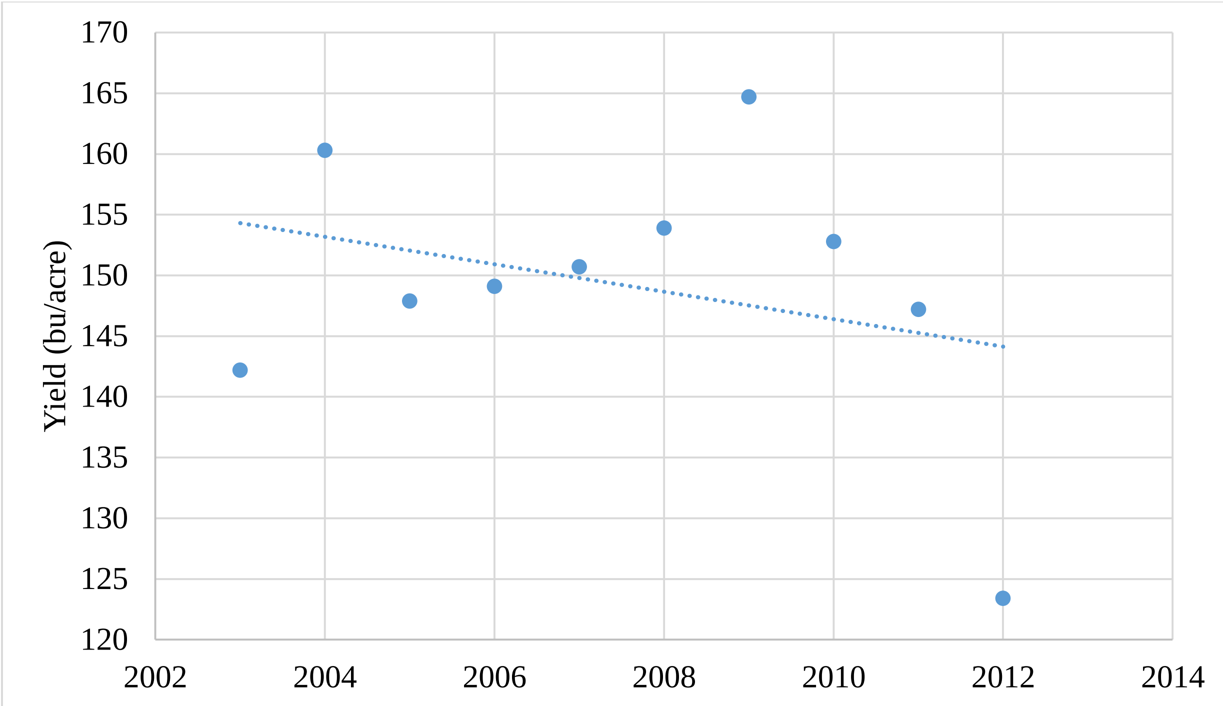

Figure 5: The inter-annual variability in yield is important to consider in LU analysis of swine production. The agricultural census data of 2012 have been recently released; however, use of those data alone would bias the study results.

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 U.S. 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 U.S. hogs are fed split-sex rations, which may impact feed conversion ratios.

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.

Live swine facility

Two types of production facilities were reviewed: conventional and hoop barn-based (Figures 6 and 7). Alternatives to these scenarios generally involve outdoor production practices and were not focused on in depth because 94% of all hogs sold in the U.S. 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

Figure 6: Conventional swine production facility (www.liquidfeeds.com, 2014)

Figure 7: Hoop barn system (www.leopold.iastate.edu/hoop-group, 2014)

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.

Production phases

Live swine production involves four distinct phases: gestation, farrowing, nursery, and grow-finish. It is common in the U.S. for some of these individual phases to take place at different facilities. For example, 29% of all hogs sold annually in 2006 in the U.S. 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 based on a production capacity of 5,200 pigs per year using the most common production phase techniques.

Table 1: Surface area requirements for live swine production facility (5,200 pigs/year)[a]

Production Phase	Building Area (m2)	Pig Area (m2/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. (2010)

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 U.S. come from farrowing crates (Purdue 2008). Recent criticism of the farrowing system has spurred an interest in suitable alternatives. Table 2 summarizes the required space for alternative systems.

Table 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 Handbook 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 U.S. 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, 2008). The use of hoop barns for gestation requires a minimum of 24 ft^2 (2.25 m^2) of bedded area per sow.

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 U.S. is 270 lb (122 kg). 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 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.

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

Figure 8: Average surface area needed per pig for each phase of production (Mcglone et al., 2010) shows the average surface area needed per pig by phases of production. All values are for group housing, except sows, which are housed individually.

Production sites

The land these facilities occupy also include access roads, a buffer area between buildings, and other green space. Lammers et al. (2010) 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

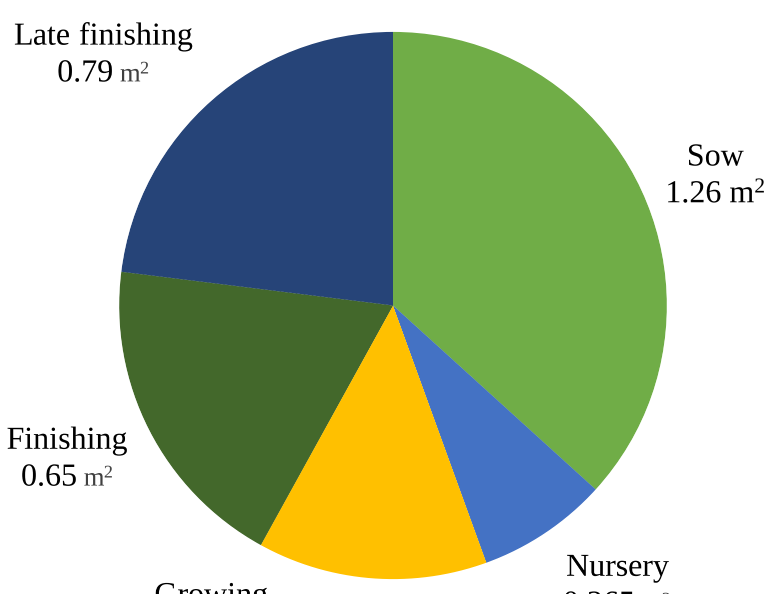

Figure 8: Average surface area needed per pig for each phase of production (Mcglone et al., 2010)

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 9 shows that larger production facilities produce more pigs per litter than their smaller counterparts, which decreases the relative land use requirement. The trend of U.S. hog production toward fewer facilities with larger inventory (Figure 10) could result in a smaller and smaller live production facility land use footprint for U.S. swine 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.

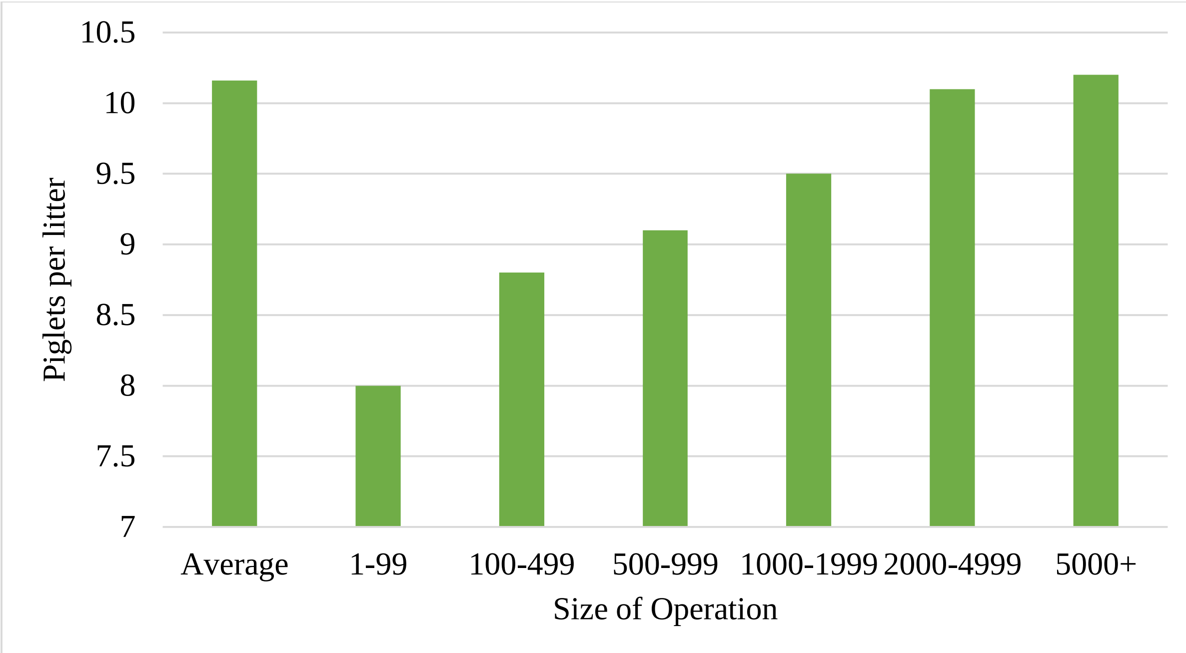

Figure 9: US pigs per litter by size of operation (NASS 2013)

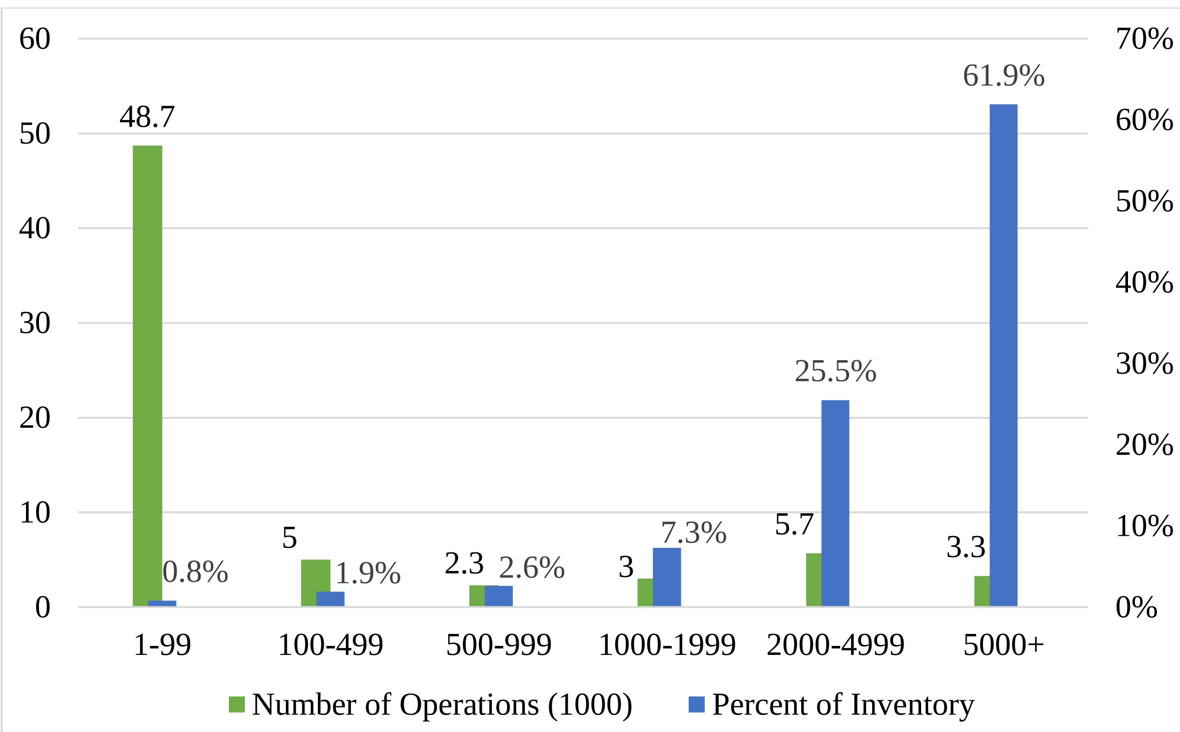

Figure 10: Number of US hog operations and percent of national inventory for 2012 (NASS 2013)

Land use impact assessment

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 (Millennium 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 (Millennium 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 U.S. 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 11 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.

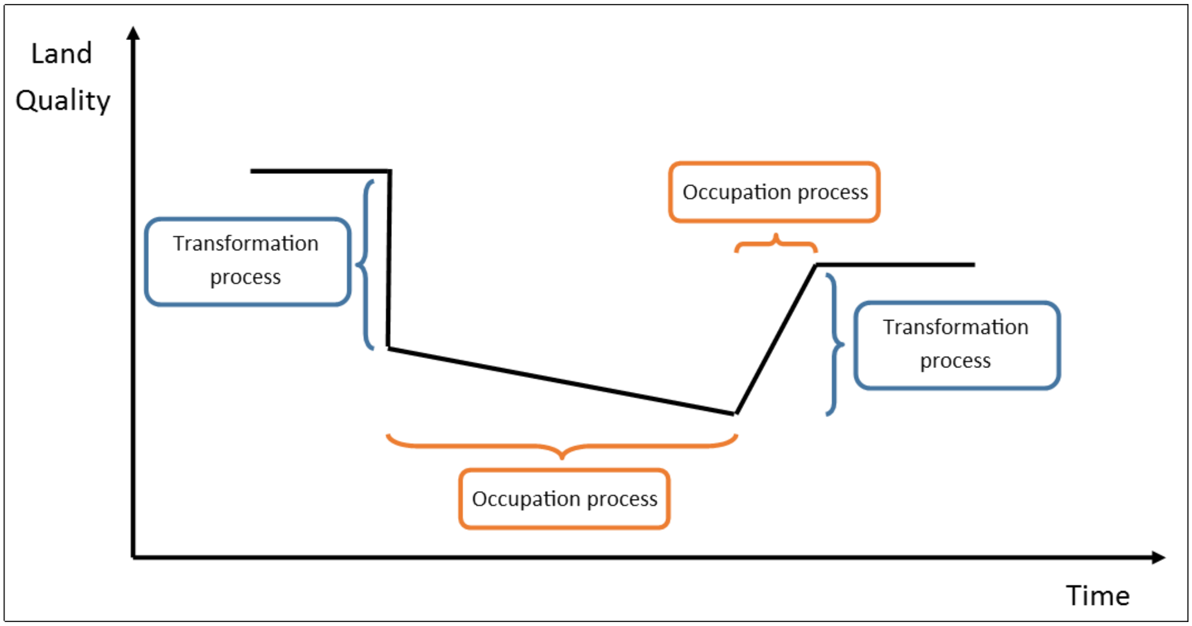

Figure 11: A simple representation of how land quality can change with use (adapted from (Lindeijer, 2000))

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. Presented here is 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.

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 capabl e of utilizing a set of characterization factors that link land use flows (land occupation and transformation) to impacts on the environment (Müller-Wenk and Brandão, 2010; Beck et al., 2011; Milà i Canals et al., 2012; Brandão and Canals, 2012; Saad et al., 2013; Souza et al., 2013; Koellner et al., 2013; de Baan et al., 2013). These impacts can be represented by the endpoints ecosystem services and biodiversity.

One of the intended impact assessment methods 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 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

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

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.

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.

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

3. MATERIALS AND METHODS

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

Goal and scope definition

The goal of this task was to conduct a detailed LCA of the U.S. pork production supply chain to quantify land use requirements. The intended audience for this assessment is U.S. 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.

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 the fertilizers used in the production of swine feed ingredients to the material components of the swine farm's infrastructure. While the principal focus of this report is land use, it also includes an assessment of trade-offs that may arise when producers use ration manipulation as a mitigation option. Figure 12 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 the land requirements associated with the raw materials used to create the swine barns.

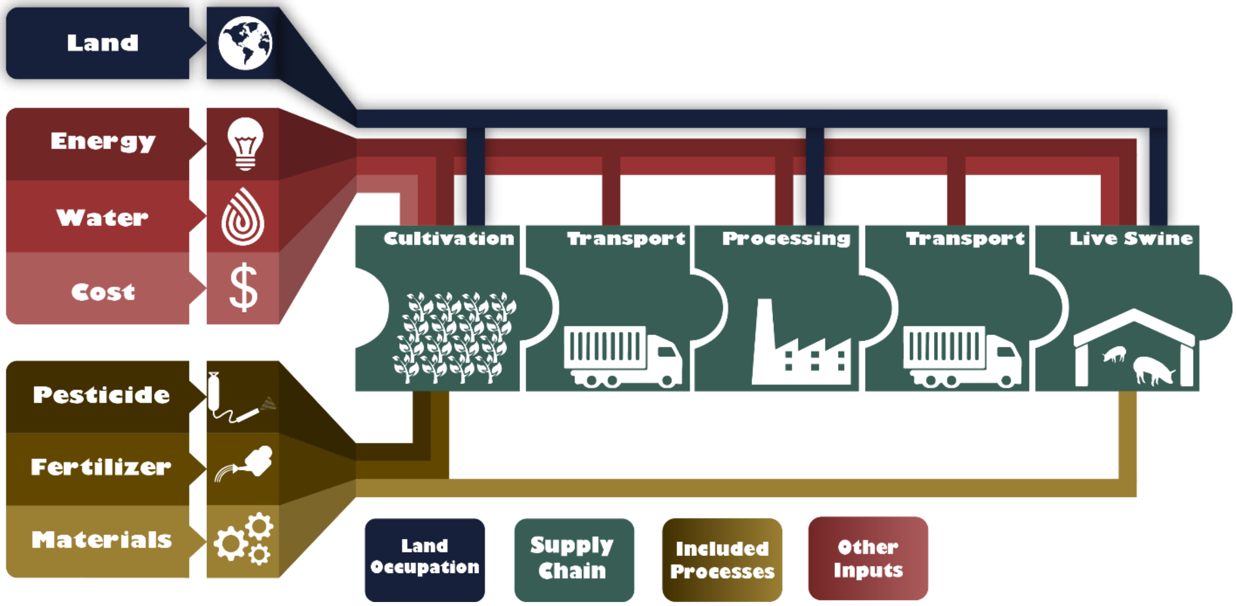

Figure 12: Process flow diagram illustrating the system boundaries for this LCA. Inputs in red are considered when comparing the tradeoffs associated with alternate ration formulations.

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.

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 feedstuffs were also used in scenario analysis. 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; Weidema et al., 2013; Blonk Consultants, 2014).

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, no distinction was made 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.

Life Cycle Inventory

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 U.S. and Region 7 covers the Southeast. In combination, these three regions represent 86% of swine production (**Error! Reference source not found.**13) in the U.S.

One county from each region was chosen to be the archetype, providing climate data and production practices typical of the production area. Table 3 shows the archetypal county from each region.

Table 3: 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

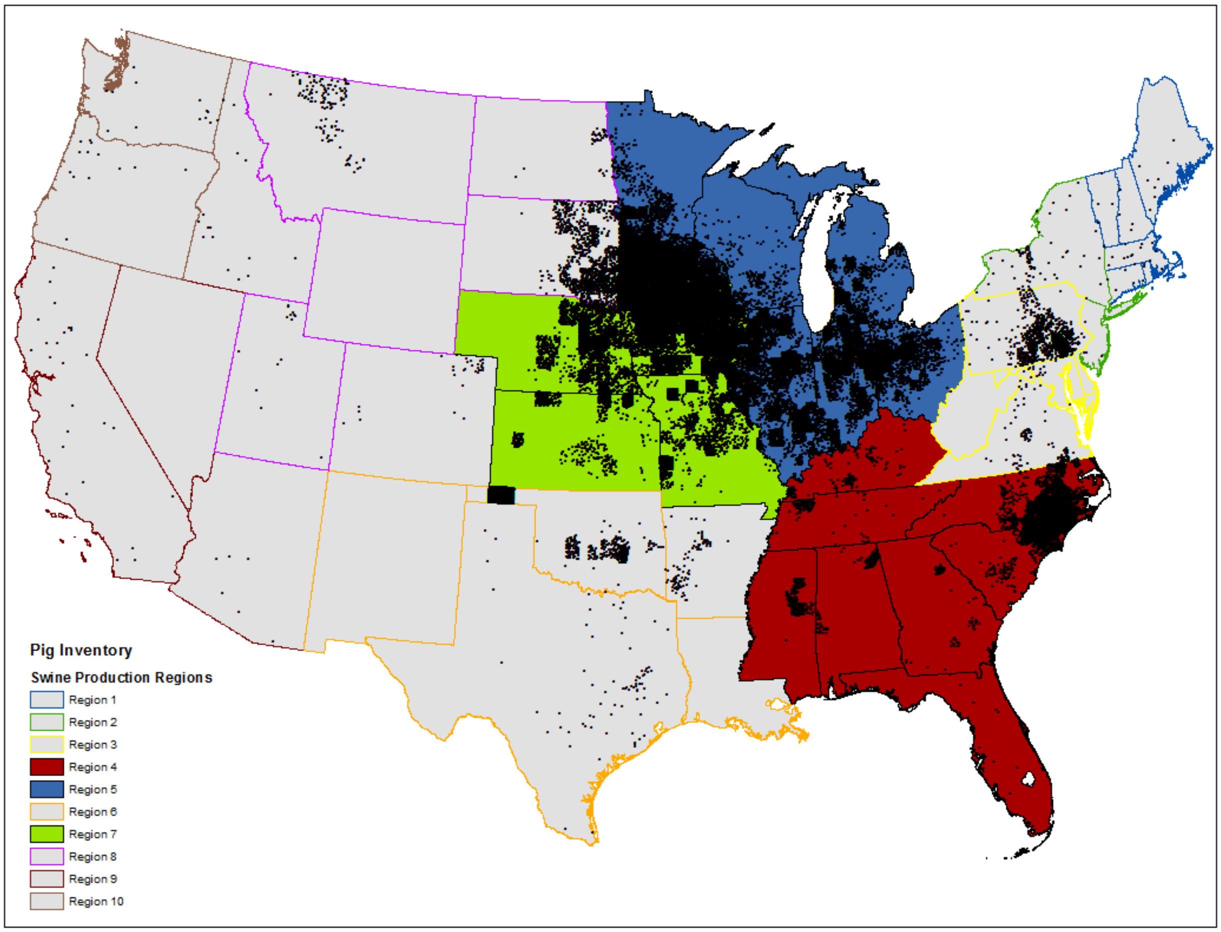

Figure 13: National swine production and the three regions assessed in this study. Each black dot represents 1400 head of swine (USDA NASS, 2012).

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 the 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.

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 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, providing an average of 3.1ft^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 – the market weight for this study. The barn provided an average of 9.6ft^2 per pig-space.

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). Demographics, and all other model inputs, are detailed fully in the Supplementary Material.

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 U.S. is attributed to production of feed rations. Therefore, seven different feed scenarios were developed in order to assess the impact associated with various ration compositions.

Baseline Scenario

The feed 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 national average swine ration.

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 trade-offs 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 U.S. 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 requirement. 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-impact diets, 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. The 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 (Pesti et al., 2008; NSNG, 2010; National Research Council, 2012). 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 diet 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 8.1 on a per kilogram of feed ingredient basis (Burek et al., 2014; PRé

Consultants, 2014). When existing data were unavailable in SimaPro, unit processes were created or modified to create U.S. national average footprints using USDA NASS census data.

The four least-impact scenarios were labeled as follows: Least Cost Scenario (LC), Least Carbon Footprint Scenario (LCF), Least Land Footprint Scenario (LLO), and Least Water Footprint Scenario (LWF). Table 4 lists all feed ingredients individually contributing more than 1% of the total ration. The four least-impact diet scenarios are hypothetical and represent guidelines for developing realistic, sustainable and cost-effective pig diets that pig producers will be able to incorporate into their production system.

Table 4: Major ration components of the four "least scenario" diets formulated by the WUFFDA model

Ingredient	LCF	LC	LLO	LWF
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%	-	-

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 to determine the effects of substituting synthetic amino acids to replace crude protein in diets 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 diet adopted from the synthetic amino acid study included sow diets. 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, slightly 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.

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.

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 U.S. pork producers (presented in the Supplementary Material). 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 U.S. 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 U.S. production was not available, European ones were used with updated values for crop yield based on national commodity averages.

Swine Farm

In order to account for land 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. The facility models assume a minimum 46 meters between each distinct phase of production and include land used for access roads. Further information on the facilities modeled can be found in the literature review.

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.

Model Development

The seven diets and all necessary input parameters were entered into The Pig Production Environmental Footprint Calculator (PPEFC), a modeling program to simulate pork production. 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, three models were created within the PPEFC: one for each of the Sow, Nursery, and Grow/Finish phases of production.

All seven scenario diets were simulated with the PPEFC for each region of production. The results produced by the calculator were then transferred to SimaPro, a software tool for life cycle modeling. All 21 combinations were then assessed based on four categories: carbon footprint (also referred to as global warming potential) (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 these are deemed to be small for US production where land has been under continuous cultivation for many decades and a majority of the shifts have been between corn and soybeans (Wallander et al. 2011). A national average for production was also assessed by combining the results of the three regional scenarios, weighted by head of swine produced annually in each region. Figure 14 presents the entire modeling process as a flow chart.

Table 5: Scenario modeling matrix.

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

Life Cycle Impact Assessment

The resulting flows from the life cycle inventory were characterized for their potential impact on climate change using the characterization model outlined by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) over a 100-year time horizon (IPCC, 2007). Characterization factors 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 characterization factors for a range of different gases. While land use is the primary impact category for this assessment, carbon footprint – 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 impact.

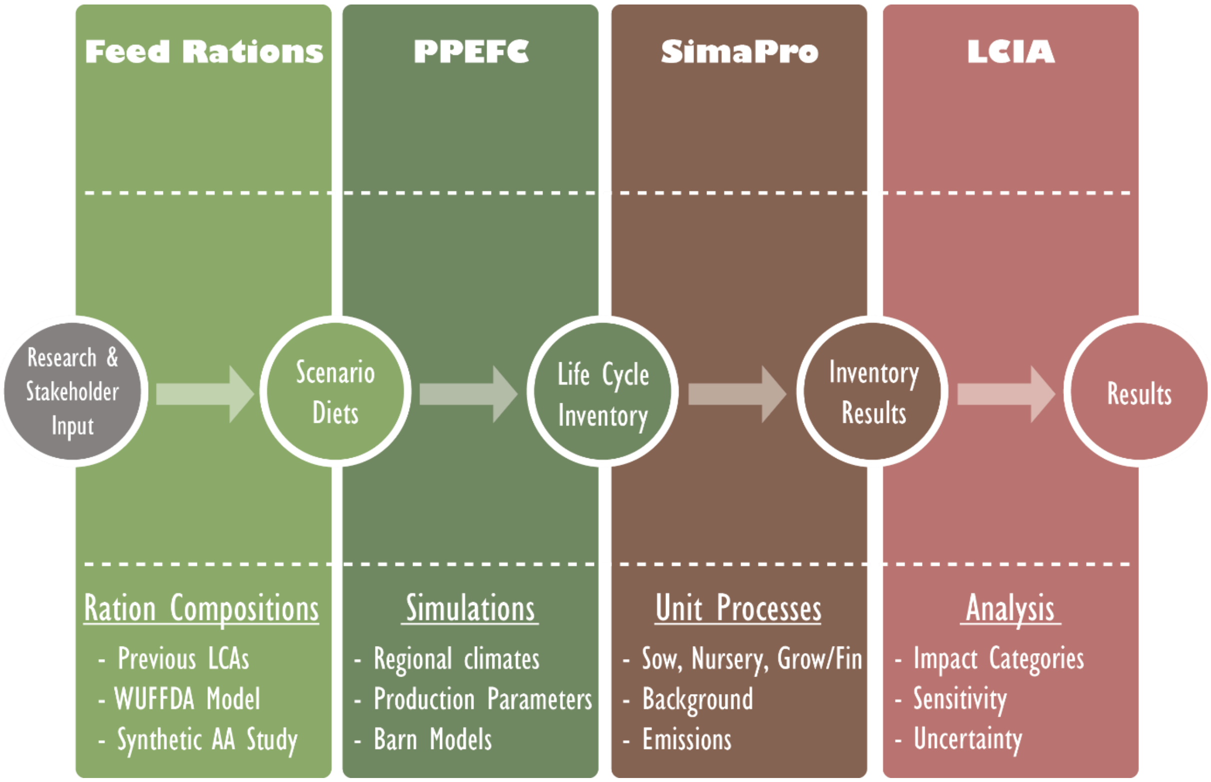

Figure 14: Process flow chart outlining the modeling process.

4. RESULTS AND DISCUSSION

Results for water use, feed cost, carbon footprint, and land occupation are shown in Table 6. The values indicate the national average for each feed scenario. The least-impact diets created by the WUFFDA model resulted in lower impact compared to the Baseline in their respective categories. The greatest impact reduction was seen in the Least Water Footprint diet for its targeted impact category of water use. For the reduced crude protein diets, increased levels of synthetic amino acids reduced feed cost and land occupation but resulted in increases in carbon footprint and water use.

Table 6: National average values for the diet scenarios and their associated impacts by category.

Scenario	Carbon Footprint (kg CO2e per kg live swine weight)	Water Use (m3 H2O per kg live swine weight)	Feed Cost (USD per kg live swine weight)	Land Occupation (m2a 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
LWF	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

“Least X” Scenario Diets

The WUFFDA model created nutritionally equivalent least-impact rations in each category. The current implementation of the WUFFDA model used is only capable of optimizing for the lowest environmental burden within a single impact category at a time. Although this approach identifies a ration with reduced impact compared to the Baseline diet, there can be significant increases in other impact categories. This is shown most clearly by the Least Water Footprint diet, which results in a 73% decrease in water use compared the Baseline. However, that diet scenario resulted in increases in cost and land occupation. The decrease in water use can be attributed to the inclusion of rotational 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 data resulting in lower national average yield, and thus in higher average land occupation.

The Least Land Occupation diet also resulted in a significant decrease in land occupation over the Baseline. When considering this diet, 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 Footprint diet. 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 diet, which resulted in a 43% increase in carbon footprint over the Baseline. Table 7 displays each scenario diet's change from the baseline for each of the four impact categories.

The Least Carbon Footprint diet 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 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 U.S. 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-impact diets, the Least Cost diet 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 diet was the only least-impact diet to produce a reduction in cost. The WUFFDA model created this diet 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 diet.

Table 7: Percent change from the baseline for each of the 4 least scenario diets 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 diet 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

Reduced Crude Protein Diets

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

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 diets are divided into two sections: national production and regional production.

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 diet over the LCPC diet. On the other hand, higher impacts were attributed to the LCP diet for water use and carbon footprint. The composition of soybean meal, corn, and amino acids in these two diets 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 diets was the same.

The LCP diet was composed of more corn, which was added to the diet 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 diet. However, higher levels of corn in the LCP diet 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 diet.

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 diet scenarios are directly compared across the four categories in Figure 15 through **Error! Reference source not found.**

Regional Production

Regional results were calculated assuming 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 U.S. 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.

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 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 U.S.

Excluding water use, the LCPC diet produced swine with lower impacts in region 7 than in region 5. However, the opposite was true of the LCP diet. 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 diet outweighs the benefits of the cooler climate in region 7. Figure 15 through Figure 18 display the national and regional results of the LCP and LCPC diet in each of the four impact categories.

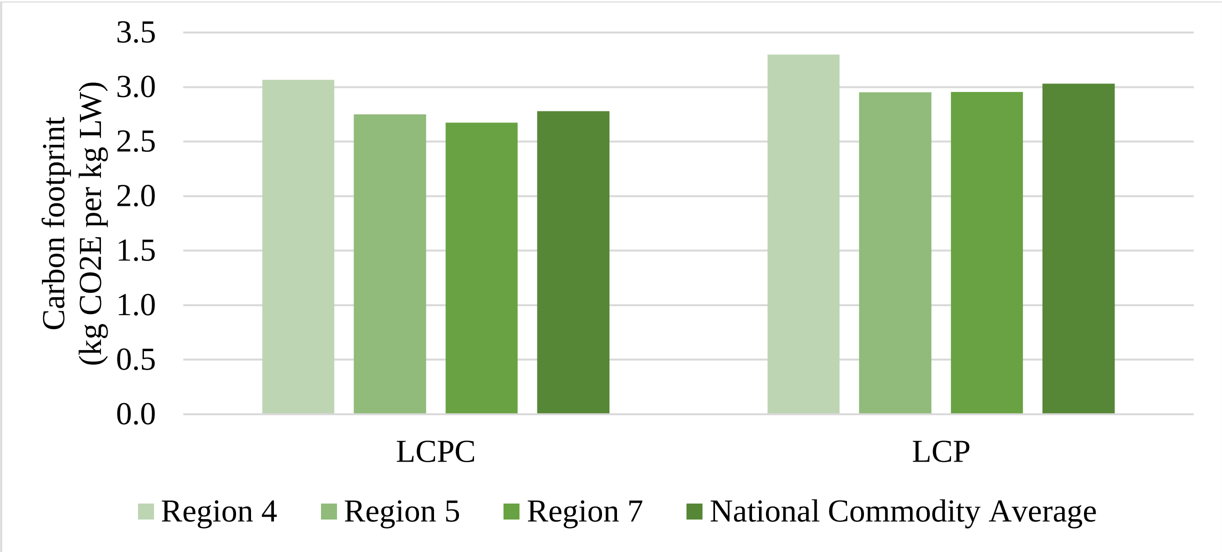

Figure 15: Carbon footprint for each region of production and as a national average using commodity feed.

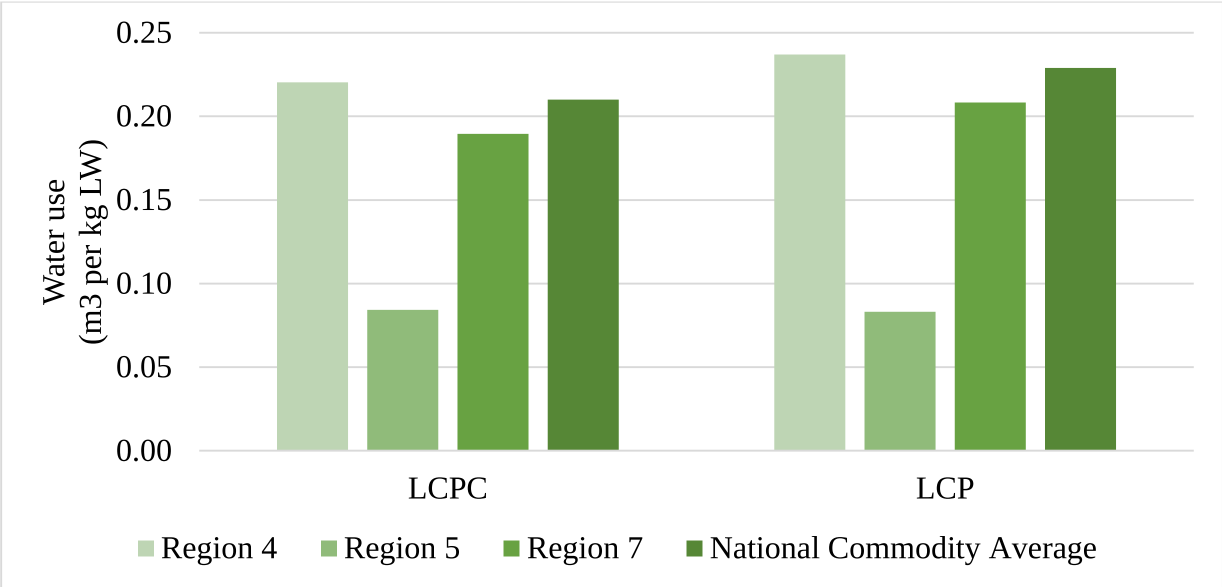

Figure 16: Water use for each region of production and as a national average using commodity feed.

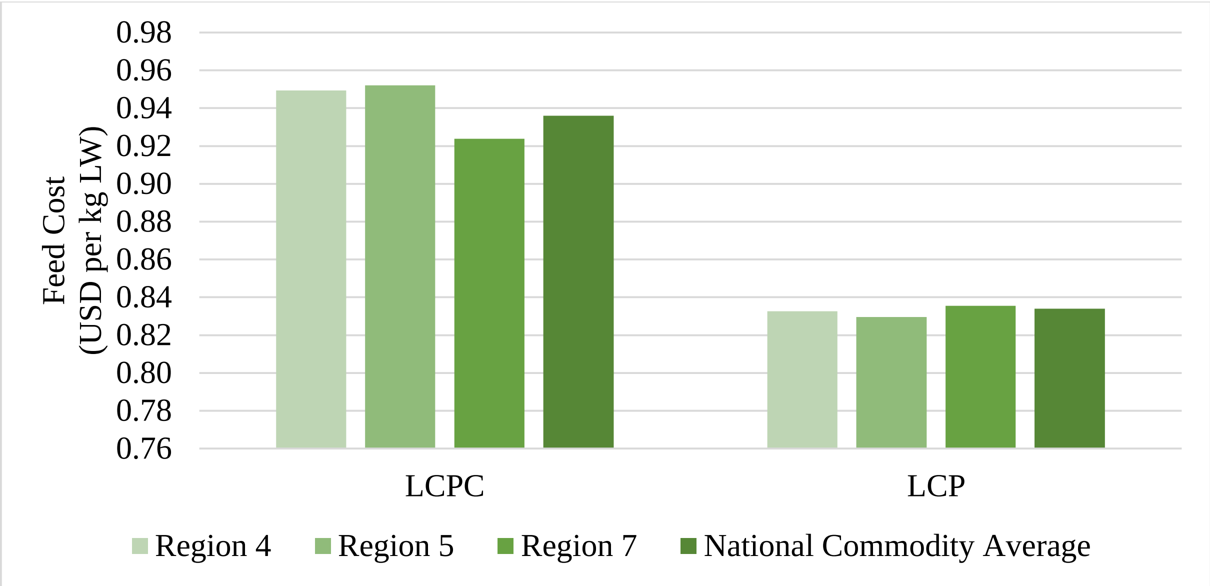

Figure 17: Feed cost for each region of production and as a national average using commodity feed

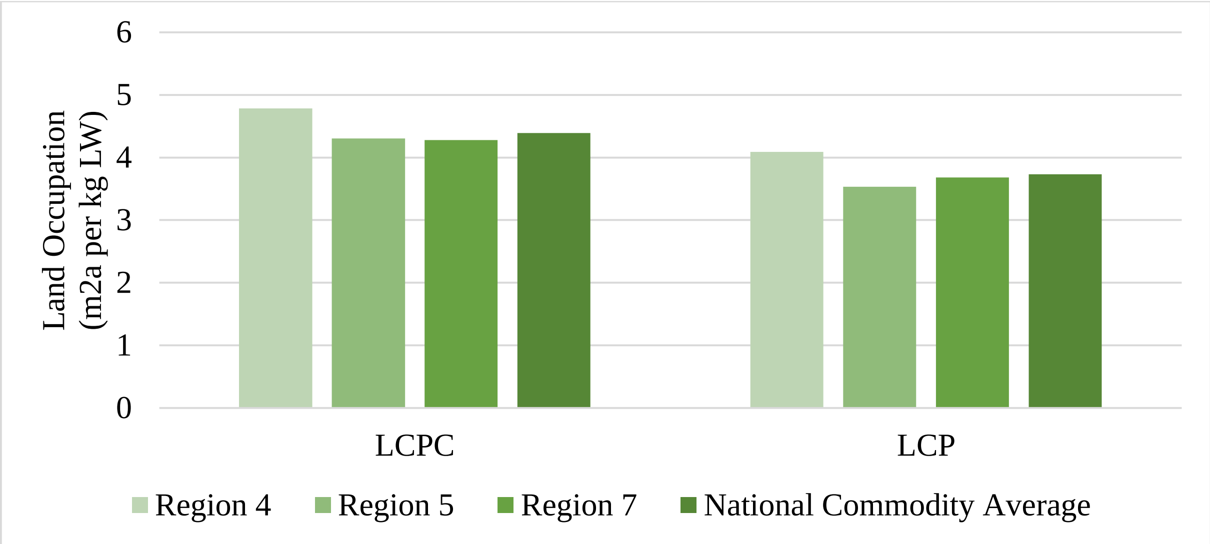

Figure 18: Land occupation for each region of production and as a national average using commodity feed.

Process Contribution

Preliminary results 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 19 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. See the Supplementary Material for a complete listing of the impact contribution from individual feed components for all seven scenarios.

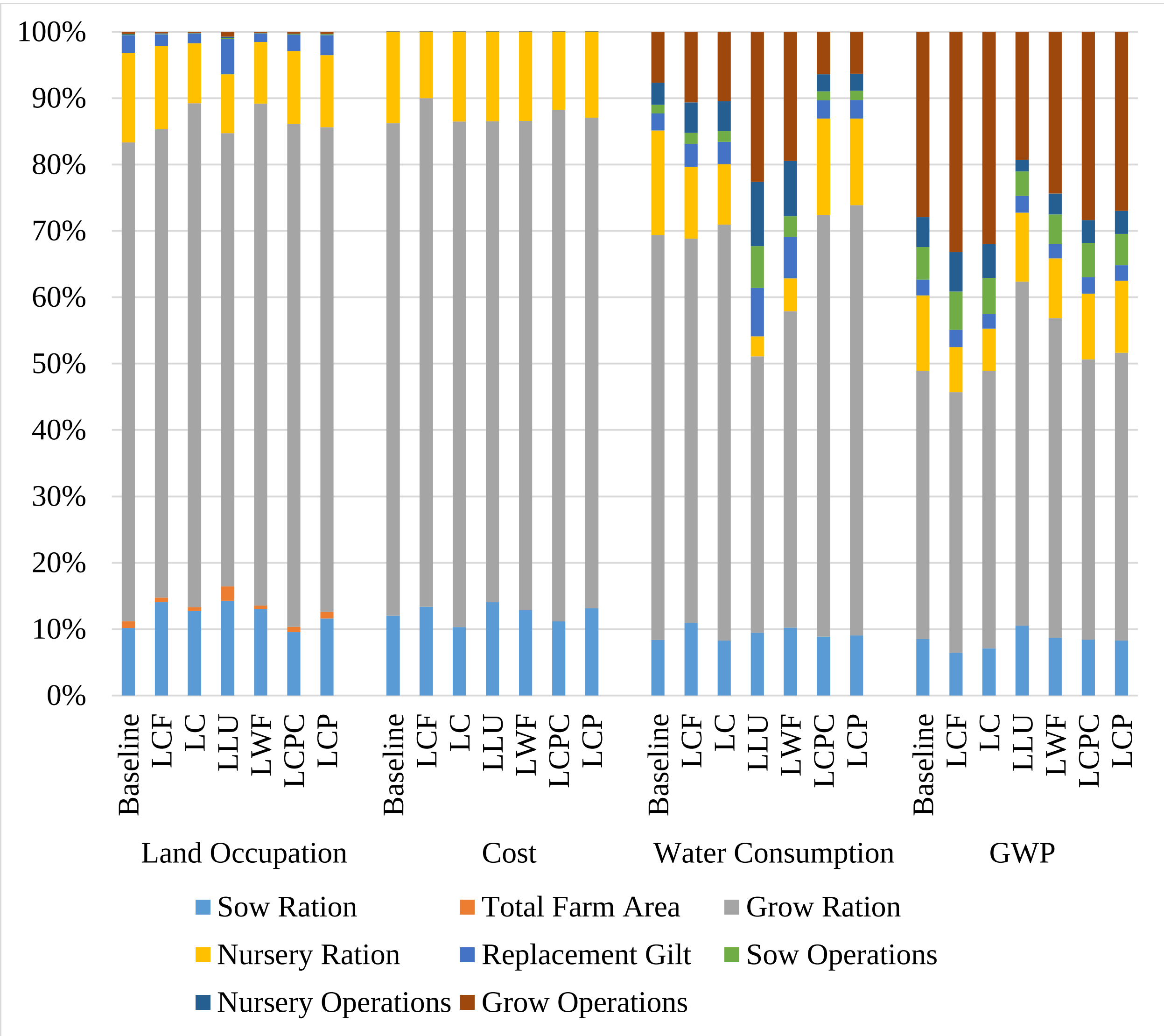

Figure 19: Potential impact contribution from each unit process across all scenarios and categories

Uncertainty Analysis

Monte Carlo simulations were performed for the region-weighted national pork production average in regards to land occupation. Results are shown in Figure 20. 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 U.S. 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-impact diet scenario vary in their ranges of uncertainty. The LLO scenario is associated with the least land occupation, while the LWF 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.

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, 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 8.

The sensitivity analysis suggests that the average U.S. 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%.

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.

Table 8: 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

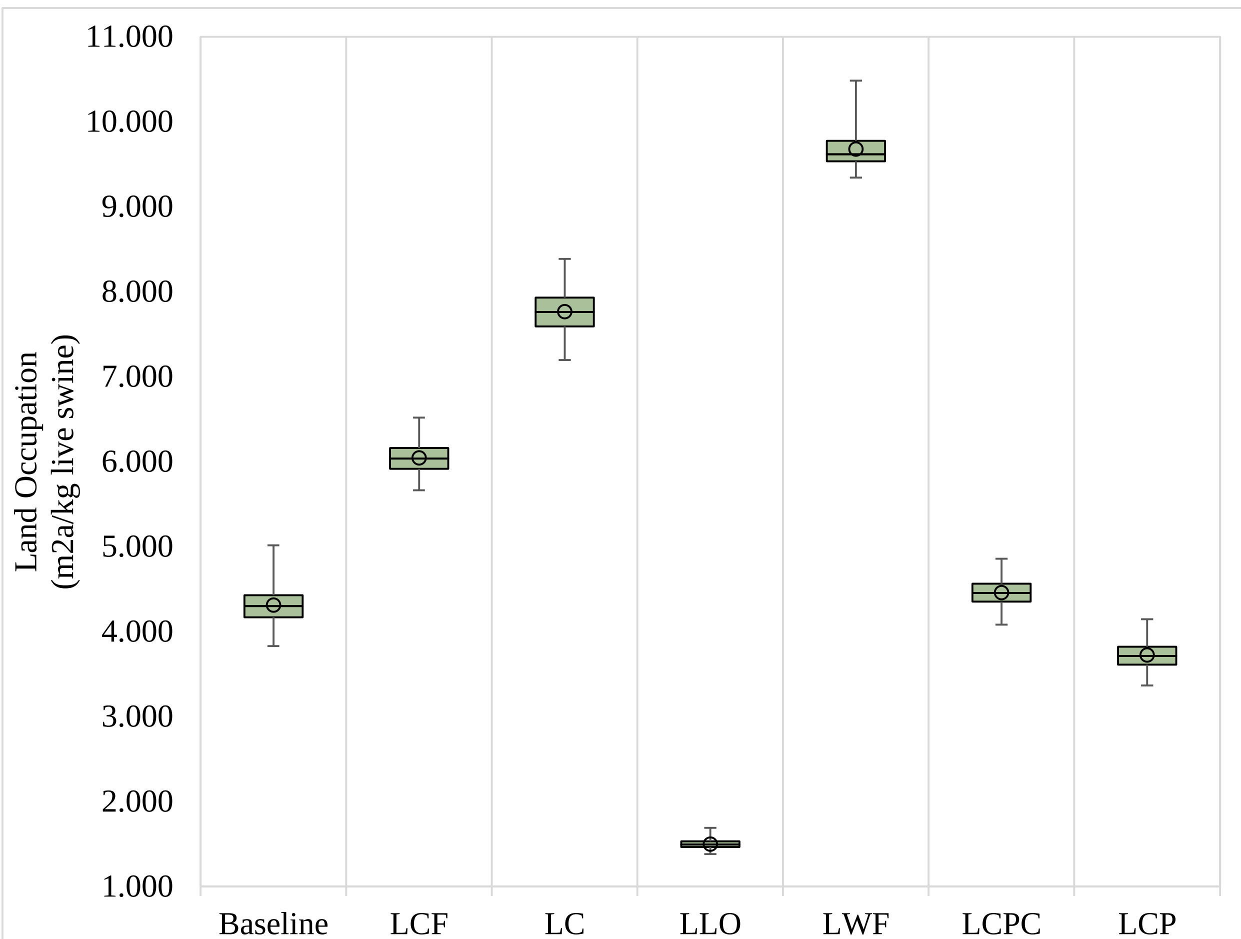

Figure 20: Uncertainty analysis of land occupation for all seven feed scenarios. The box represents 25th and 75th percentile of 1000 Monte Carlo runs, the centerline represents the median, the whiskers indicate the minimum and maximum, and the circle represents the average.

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 Figure 22. 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 21 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. A complete list of ingredients that required allocation is provided in the Supplementary Material.

In 93% of cases, the economic allocation of feed by-products 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 diets were less sensitive to allocation methods than the least-impact diets. They more closely resemble a typical swine ration for U.S. production, which only contain two or three products with allocated burdens. The least-impact diets showed greater variation between methods, most notably the Least Land Occupation and Least Water Footprint diets. The more coproducts included in the diet generally led to increased sensitivity to the allocation method. For example, the Least Land Use scenario diet was composed of 11 coproducts and the land occupation associated with this diet ranged from 2.15 m^2a/kg LW (economic) to 5.12 m^2a/kg LW (mass). Compare that to the Baseline diet, which had only two coproducts and ranged from 4.21-4.68 m^2a/kg LW (economic-mass).

In agricultural lifecycle assessment, economic allocation for the byproducts is the most commonly used approach. As shown in Figure 22, 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.

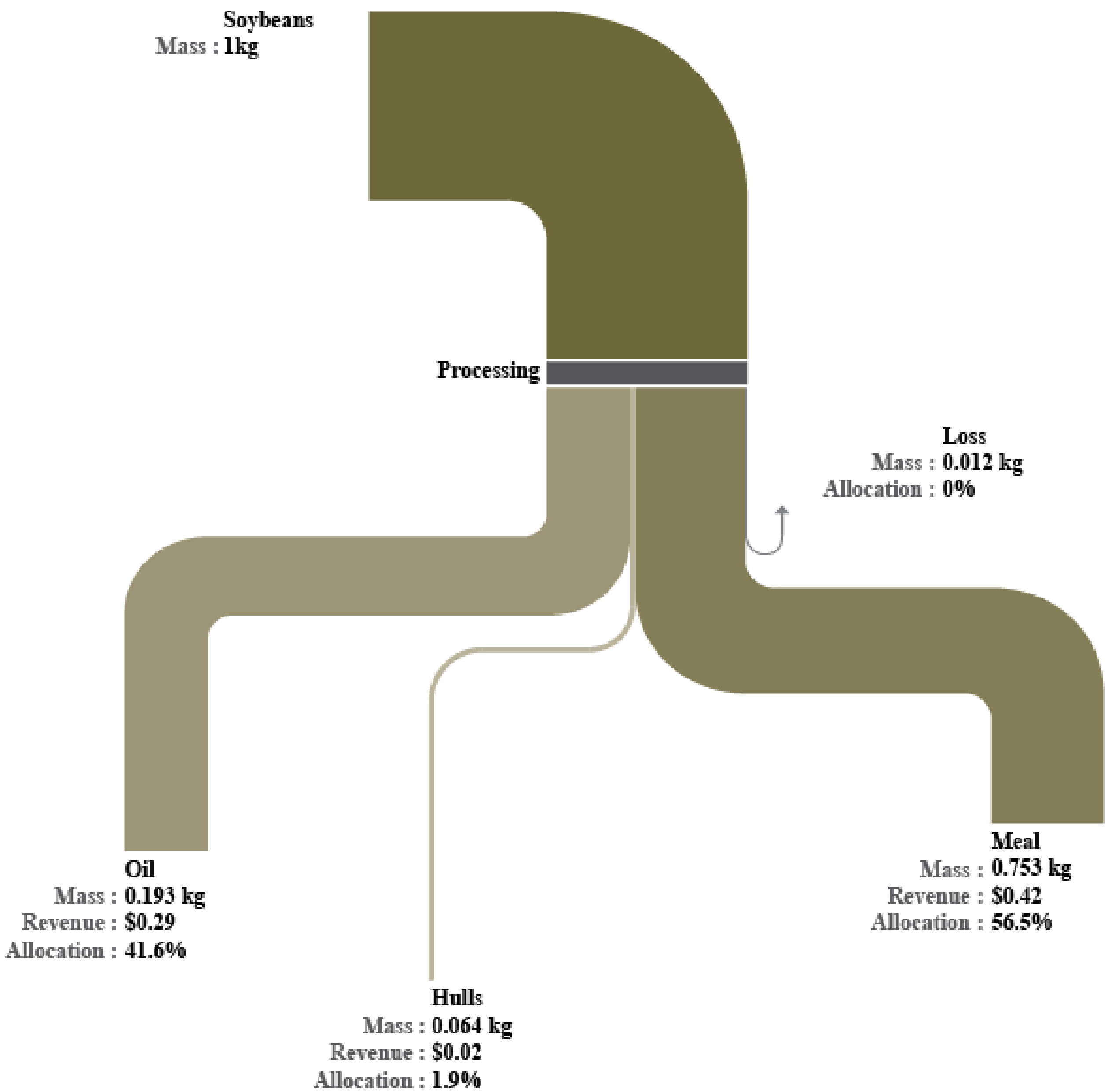

Figure 21: Allocating burdens according to their economic value. The revenue values are based on price per kilogram (Burek et al. 2014).

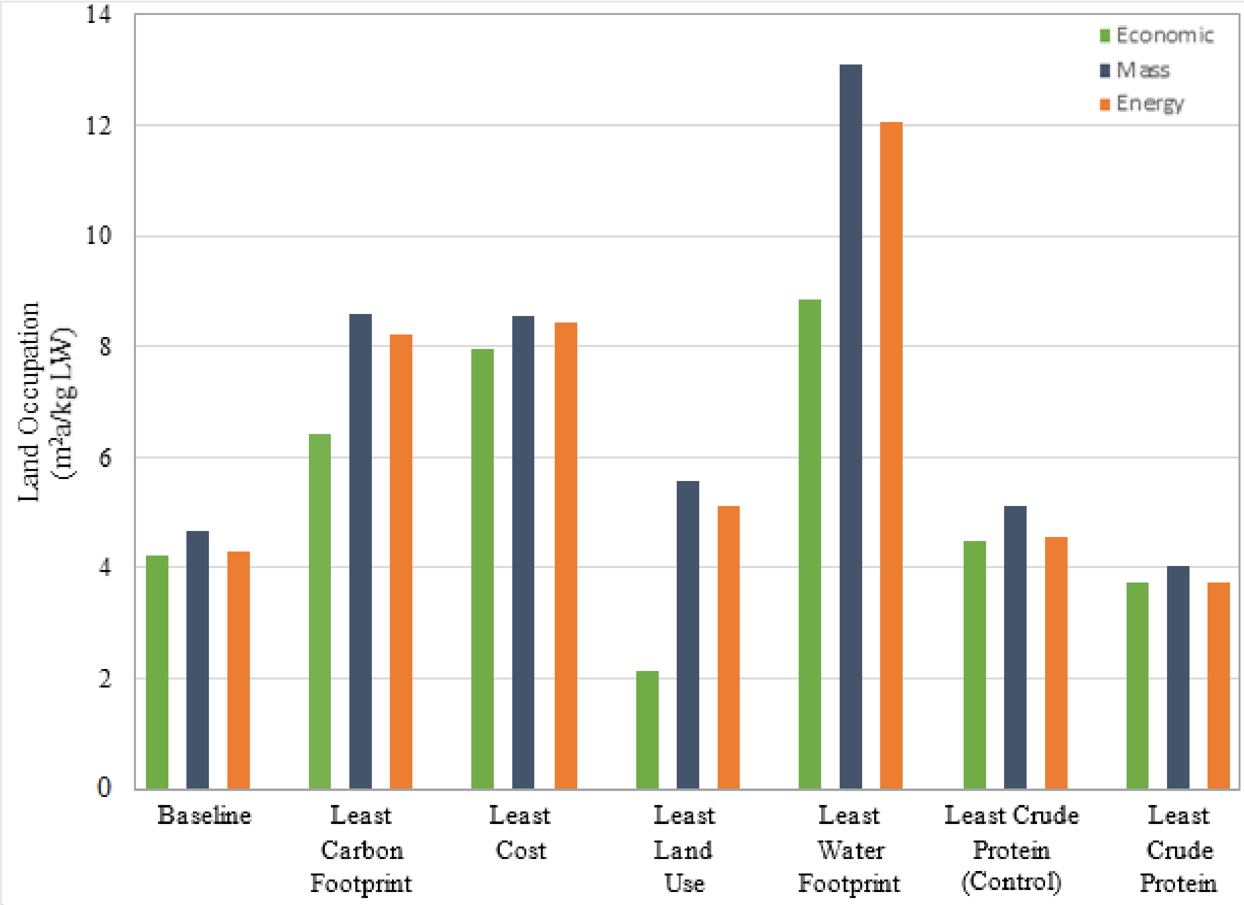

Figure 22: Sensitivity results from three different allocation methods on all scenario rations.

Statistical Analysis of Hypotheses

Analysis of variance and paired T-tests were conducted on the results of this assessment in regard to the three hypothesis statements established at the onset of this assessment. Statistical analysis was performed using JMP Pro 11.0 software (SAS Institute, 2013). The hypotheses are restated below.

H(0)1: All nutritionally-equivalent swine feed rations have approximately the same land footprint.

H(A)1: Some nutritionally-equivalent swine feed rations have a larger footprint than others.

H(0)2: Methods for allocating environmental impact have no effect on land footprint.

H(A)2: Land footprints are affected by allocation methods.

H(0)3: All regions of swine production have approximately the same land footprint.

H(A)3: Land footprints vary with the region of production.

Sufficient statistical evidence was provided in two of the three statements to reject the null hypothesis (Table 9). Nutritionally-equivalent swine feed rations and methods for allocating environmental impact significantly affected the land footprint associated with swine production. The region of swine production was not proven to have a significant impact on land use.

The paired T-tests for region of production showed significant difference between producing swine in region 4 and region 7, but not between regions 5 and 7. The analysis of variance showed no significant effect on land use. It is possible that only testing for three regions was not enough data to prove significance.

Method of allocation was shown to have a significant effect on the land footprint of swine production ($p < 0.0001$). Allocating by mass consistently resulted in the highest land occupation and economic was consistently the lowest.

Statistical analysis also proved that some nutritionally-equivalent swine feed rations have a larger footprint than others ($p < 0.0001$). Regardless of method for allocating impacts, the LWF feed scenario had the largest associated land occupation. The LCP scenario was typically the least consumptive in terms of land use, except for the LLO scenario when allocating burdens economically.

Table 9: Results from the analysis of test on the three hypothesis statements

Effects Tests					
Source	**N**	**DF**	**Sum of Squares**	**F Ratio**	**Probability > F**
Region	2	2	4.35057	2.2945	0.1109
Allocation	2	2	41.71272	21.9996	< 0.001
Scenario	6	6	400.06544	70.3324	< 0.001

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 U.S. 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.

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