

# A Life Cycle Analysis of Water Use in U.S. Pork Production

## Comprehensive Report



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## Glossary of Terms

Blue Water	Available surface or groundwater that can be distributed to and competed for by multiple end users. Only blue water was quantified throughout this LCA
Green Water	Water from on-land precipitation that remains in or on top of the soil and eventually evaporates or transpires through vegetation. Excludes infiltration that recharges groundwater
Cradle-to-Grave Analysis	Life Cycle Assessment with system boundaries that include the farm, retail, and consumer use and disposal phases of a product
Functional Unit	Defines the unit of product or service for which life cycle impacts will be assessed during a Life Cycle Assessment
Life Cycle Assessment	Quantitative analysis of a complex system for the evaluation of the impacts and risks associated with the production system
Life Cycle Impact Assessment	Step in an LCA in which the human and/or environmental effects of material consumption and environmental releases within a production system are quantified
Life Cycle Inventory (LCI)	Step in an LCA in which all of the relevant flows of materials, products, and energy into and out of a production system are quantified
Breeding/Gestation	Pig life phase when a gilt (female pig that hasn't given birth) or a sow is bred with a boar or artificially inseminated and is pregnant for approximately 16 weeks
Farrowing/lactation	Pig life phase when a sow gives birth to piglets that feed from the sow until approximately 10-15 lb or 3 weeks when they are weaned
Nursery	Pig life phase after piglets are weaned from a sow and live in a nursery facility until they are nine weeks old or 40-60 lb
Grow/finish	Pig life phase after nursery where pigs stay until they reach market weight (approximately 275 lb). Sometimes these phases occur in a single barn but they can also be split into a grow barn followed by a finishing barn

# Executive Summary

The goal of this study was to analyze water use in the U.S. pork industry using Life Cycle Assessment (LCA) methodology. LCAs are quantitative analyses of complex systems for the evaluation of impacts and risks associated with management decisions. LCA can be an effective tool for determining comparative advantages of management strategies across specific environmental impacts of concern.

The environmental impact category that was used in this assessment to evaluate processes throughout the pork supply chain was cumulative water use (gallons). This assessment was performed at two scales: a cradle-to-grave scan-level analysis and a cradle-to-farm gate detail-level analysis. The Pig Production Environmental Footprint Calculator (PPEFC) was enhanced with water consumption algorithms based on data from peer reviewed scientific literature. The PPEFC was then utilized to estimate the lifecycle inventory of water use. The work on this project was divided into the following tasks:

- Task A. Literature Review for Water Footprints
- Task B. Pork Supply Chain Scan Level LCA of Water Use
- Task C. Live Swine Production Detailed LCA of Water Use
- Task D. Pig Production Environmental Footprint Calculator

## Literature Review

The goal of the literature review was to gather water use information for the U.S. Pork Industry from field-to-gate. The findings from the literature review, together with discussions with industry experts, were used to create the Life Cycle Inventory (LCI) and provided the input data needed for the production system models. The literature review also provided the information used to create water use algorithms for the PPEFC.

Review of the literature revealed that nearly 70% of the water footprint could be attributed to crop irrigation water when using low resolution global datasets. The provenance of the feed crops can drastically affect the associated blue water (available surface or groundwater that can be distributed to and competed for by multiple end users) footprint of the crops, but spatially explicit feed crop water use literature for the U.S. was rare. We were compelled to use NASS survey data and Farm and Ranch Irrigation survey data to derive state level water consumption estimates for the most common feed crops. Adequate literature was available for the major on-farm water use contributors such as drinking water, cooling water and washing water. Higher resolution feed production LCAs and knowledge of the feed provenance for specific operations will increase the accuracy of animal product footprints.



## Scan-Level Life Cycle Assessment

The scan-level LCA was a cradle-to-grave water footprint analysis of the production, distribution, and consumption of U.S. pork across 10 USDA production regions (Figure ES.1). The functional unit for this assessment was a four ounce serving of undefined boneless pork prepared for consumption by a U.S. consumer.

Overall, the U.S. pork water footprint was estimated to be 8.2 gal/4oz (0.031 m<sup>3</sup>/4oz) serving of boneless pork with a total pork industry water use of 525,000,000,000 gal/yr (1,990,000,000 m<sup>3</sup>/yr) when analyzed using a weighted ration (that is based on a nationally weighted crop production). As part of the sensitivity/scenario analysis, each of the ten regions was analyzed with three scenarios; once with the commodity swine rations, once with regionally sourced rations, and finally using a weighted ration calculated using estimated contributions (that is mixtures) of commodity and regional feed consumption by region to produce the most likely footprints for each region.

The feed ration footprint accounts for 83% to 93% of the entire pork supply chain footprint depending on the feed source. This is mostly water used to irrigate crops in the field. Feed crop water footprints can vary over 100 times in magnitude from one region to another. The second largest contributor to the total water footprint was on-farm activities with 5% to 13%, while post-farm-gate activities contributed 2% to 4% of the total water footprint. There is opportunity at the consumer phase for post-farm gate water savings through more efficient dish washing since dish washing makes up 90% of the consumer's water footprint and approximately 1% of the cradle-to-grave footprint. Ultimately, sourcing rain-fed feed crops rather than irrigated feed crops would lead to the largest reduction in the pork industry's water footprint.

## Detailed Life Cycle Assessment

This assessment was a cradle-to-gate (live swine ready for transport to processing) analysis of the water footprint of U.S. pork production at a higher resolution than the scan-level. The functional unit for the detailed LCA was defined as one pound of swine (live weight) at the farm gate. The various production scenarios analyzed in the detailed level LCA are shown in Table ES.1. In this LCA, all scenarios used the same commoditized ration and its inherent water footprint.

The detailed analysis showed water use ranged 18.38-18.94 gal/lb<sub>live weight</sub> (0.153-0.158 m<sup>3</sup>/kg<sub>live weight</sub>) across production strategies and regions. The tunnel ventilated barn water footprint was consistently higher, followed by the drop curtain and then the hoop barn in each of the regions. It should be noted that the differences between barn types was driven by the assumed cooling systems used. For example, tunnel ventilated barns were assumed to use the most water based cooling systems whereas hoop barns were assumed to have no water based cooling systems. Although the hoop barn has been shown to use less water in hot regions, this may be misleading because animal performance is likely to suffer during periods of extremely hot weather without dedicated cooling systems.

The greatest water footprint was from regions in the south (Regions 4, 6, and 9) due to the increased use of water based cooling systems as a consequence of higher temperatures. (Figure ES.1). When considering the total water use by production phase, the Grow/Finish phase accounted for approximately 75% of the footprint (including feed production) when compared to the sow and nursery life phases. The water embodied in the feed drove the grow/finish phase to have a larger footprint since that life phase required the most feed. The larger scale facilities had marginal decreases in water footprint due to increases in piglets per litter, which distributes the sow's footprint across more pigs, and improved climate control efficiencies.

Overall the results show that rations account for approximately 90% of the cradle-to-gate water footprint. Cooling water and washing water were not insignificant contributors to the water footprint, but they are relatively small and are not likely to be easy opportunities for improved efficiency. Drinking water is the second most significant contributor to the water footprint, and represents 9% of the total cradle-to-gate water footprint and 87% of the on-farm water footprint. Therefore, improved on-farm water efficiency techniques would have a significant impact on the total water footprint, especially reductions in the amount of water wasted from drinking systems. As stated in the literature review, replacing nipple drinkers with cup style drinkers placed at the appropriate height could reduce drinker water use by 20-31% and thus reduce the cradle-to-gate water footprint by 1.8-2.7%.

Table ES.1 Scenario matrix of Live Swine Production Water Use LCA.

Production Strategies	Production Scale	Life Stage	Production Region (Figure ES.1)
Drop Curtain	100	Sow (BGL)	Region 1 (CT ME NH VT MA RI)
Tunnel Ventilated	1200	Nursery	Region 2 (NY NJ)
Hoop Barn	2500	Grow/Finish	Region 3 (DE MD PA WV VA) Region 4 (AL FL GA KY MS NC SC TN) Region 5 (IL IN MI MN OH WI) Region 6 (AR LA NM OK TX) Region 7 (IA KS MO NE) Region 8 (CO MT ND SD UT WY) Region 9 (AZ CA HI NV) Region 10 (AK ID OR WA)

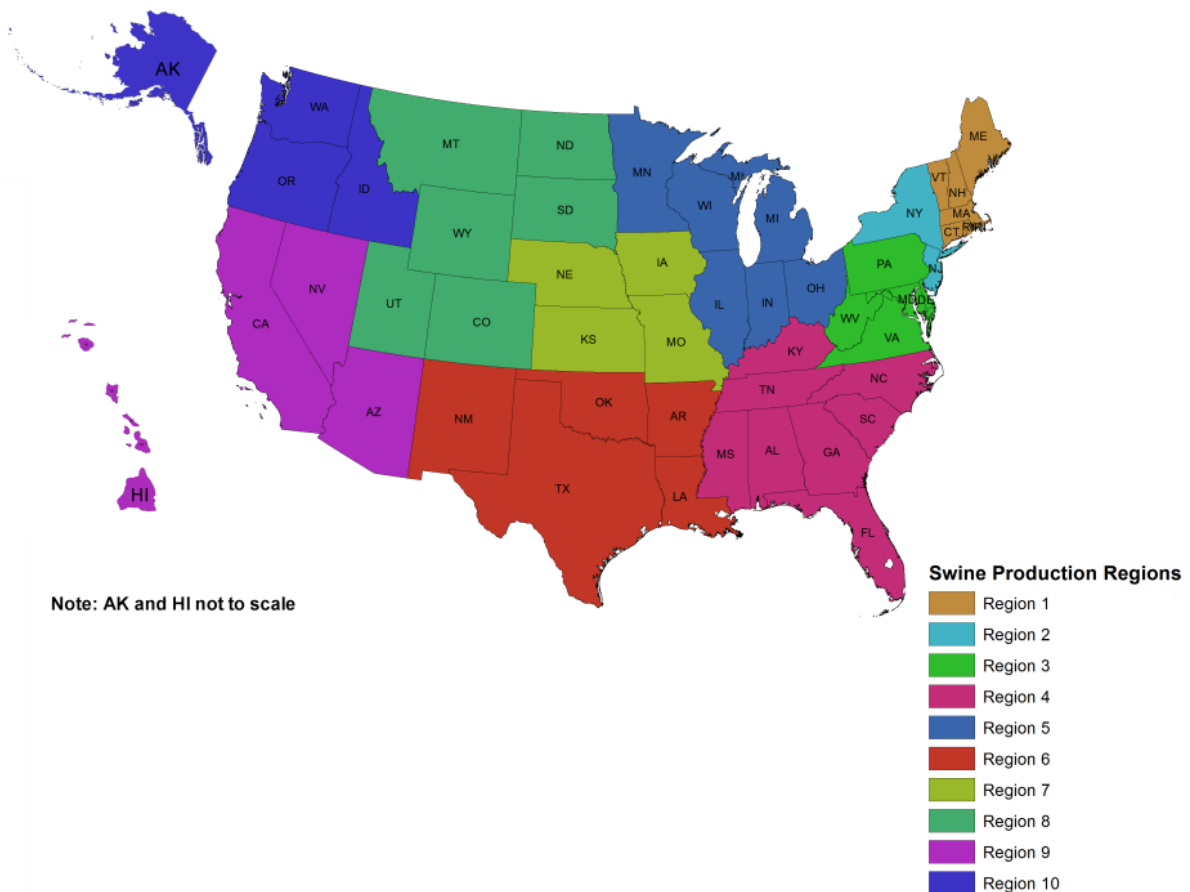


Figure ES. 1. Regions used in the scenario analysis for U.S. pork production.

# Chapter 1. Literature Review

## 1.1. Introduction

The goal of this study was to analyze water use in the U.S. pork industry using life cycle assessment (LCA) methodology. LCAs are quantitative analyses of complex systems for the evaluation of the impacts and risks associated with a production system. LCA can also be an effective tool for determining comparative advantages of management strategies across specific environmental impacts of concern. An LCA of water use within the pork industry was performed, and a Pig Production Environmental Footprint Calculator (PPEFC) was enhanced with water consumption algorithms based on data from peer reviewed scientific literature. The work on this project was divided into the following tasks:

Task A. Literature Review for Water Footprints

Task B. Pork Supply Chain Scan-Level LCA of Water Use

Task C. Live Swine Production Detailed LCA of Water Use

Task D. Pig Production Environmental Footprint Calculator

This sub-report presents the results of the literature review (Task A). The goal of this literature review was to gather information on water use in the U.S. Pork Industry from field-to-gate. The findings from the literature review, together with discussions with industry experts, were used to create the Life Cycle Inventory (LCI) and provided the input data needed for the production system models. This literature review also provided the information used to create water use algorithms for the PPEFC.

## 1.2. Overview of Water Use in Swine Production

This review includes water use information for feed and swine production for the processes shown in Figure 1. Each arrow in the diagram represents a range of water use to or from each unit process. The instances where water was used for each phase of the pork life cycle, with additional detail placed on the processes from the field to the farm gate are shown in Figure 2. Only the quantity of blue water was considered throughout this LCA. In addition, consideration of water quality impacts was beyond the scope of this study.

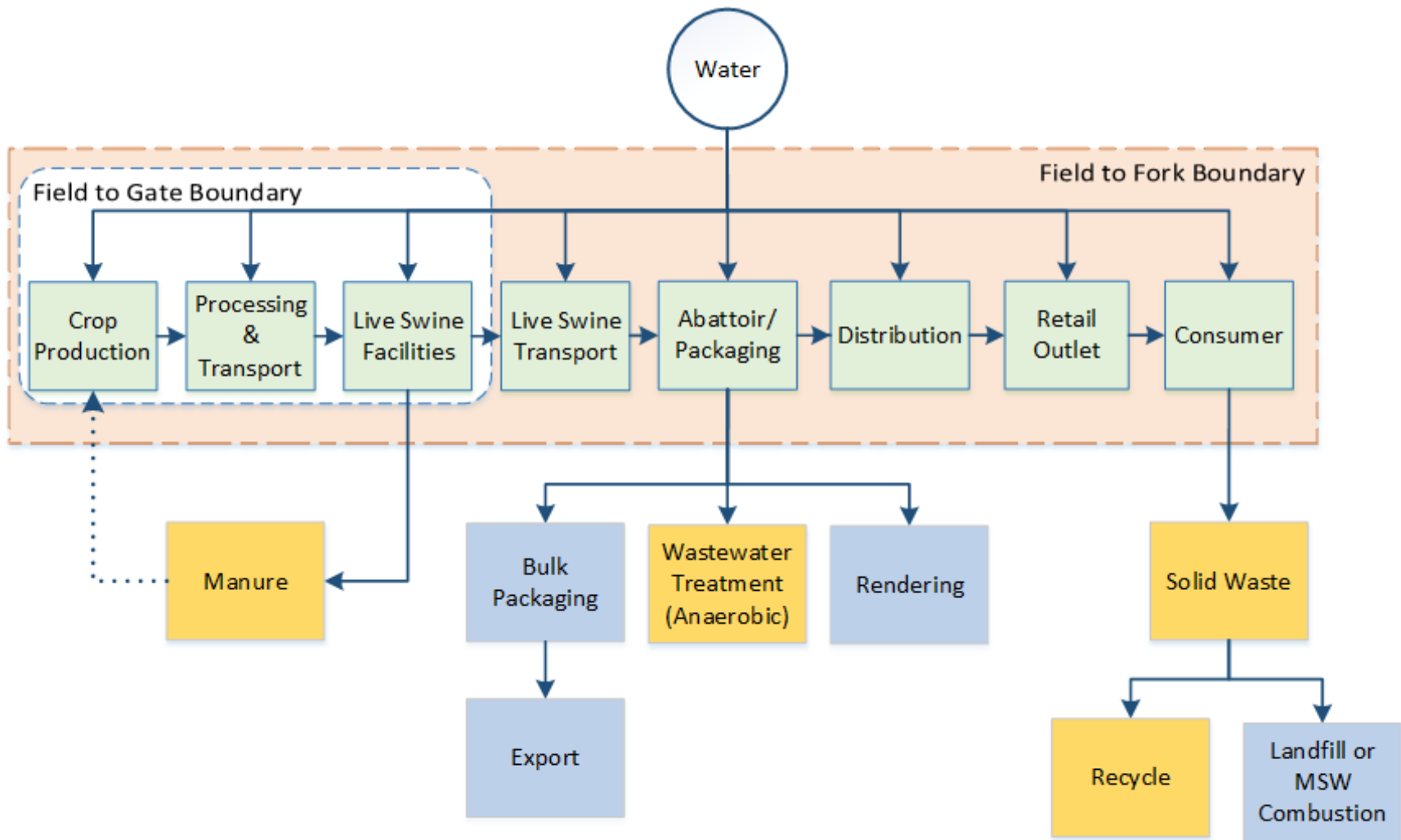


Figure 1. Process flow diagram of the entire U.S. pork supply chain with water inputs.

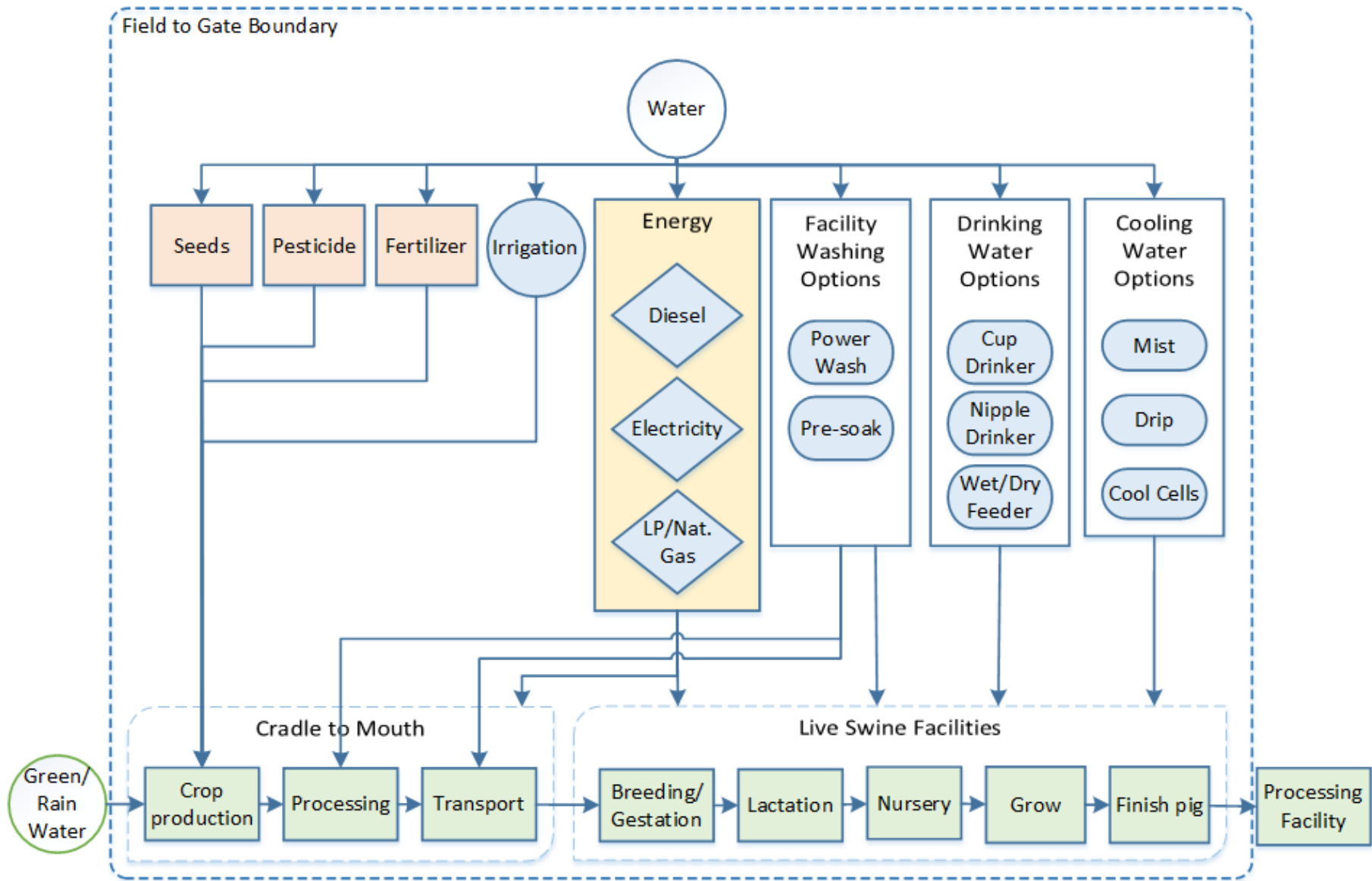


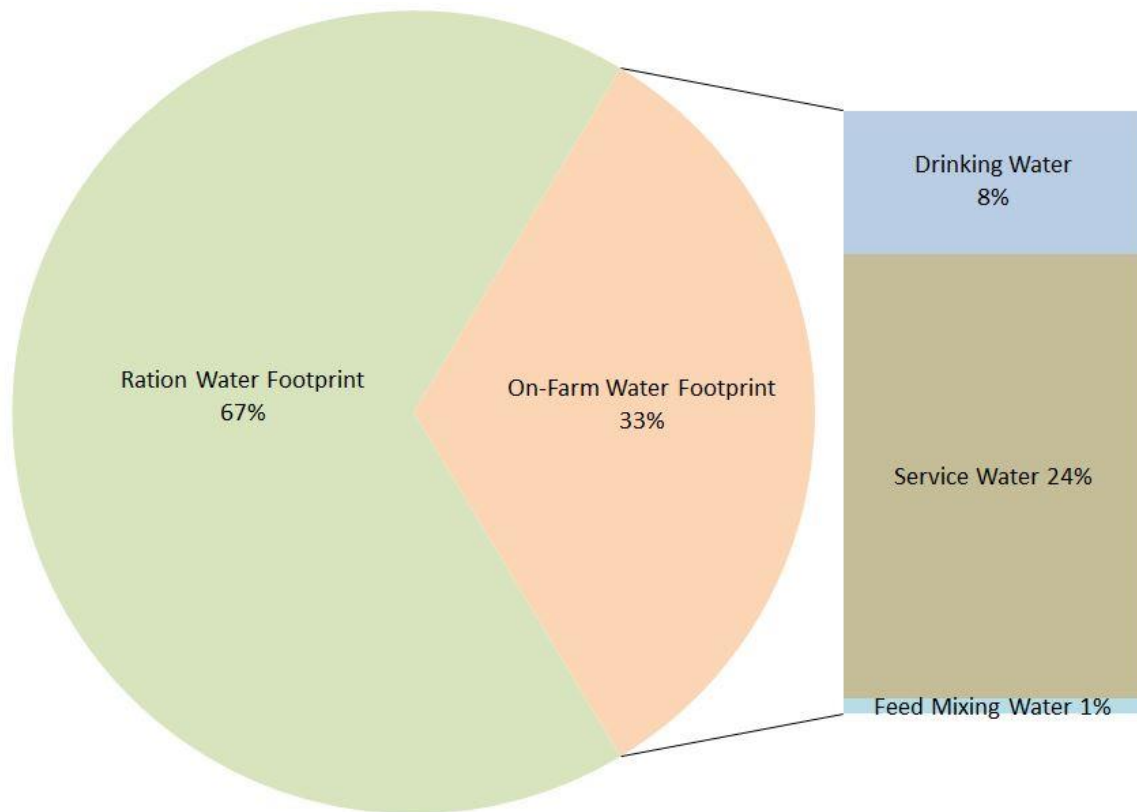
Figure 2. Process flow diagram for the field-to-gate boundary for water utilization analysis.

### 1.2.1. Water Use from Cradle to Farm Gate

All of the water consumption that occurs from crop production, through the live swine facility, and to a market ready pig was considered to be the “cradle-to-gate” water footprint. The boundary of water utilization in pork production processes from field to gate is shown in Figure 2. The largest components of water consumption in the pork production process are crop production for feeds and the live swine production facilities.

### 1.2.2. Water Use in Crop Production

When considering water use in the U.S. pork production, the majority has been shown to come from irrigation of feed crops (Figure 3). Of the water used directly in the live swine production facilities (see Figure 4), the majority is the consumption of service water and drinking water by the animals. Service water is defined as the water used in facility cleaning, animal cooling, etc.



*Figure 3. Distribution of blue water use in U.S. pork production (excluding post-farm gate). Service water refers to cleaning water, washing water, and other services necessary to maintain environment. Ratios were calculated based on global datasets and methods from Mekonnen & Hoekstra (2011).*

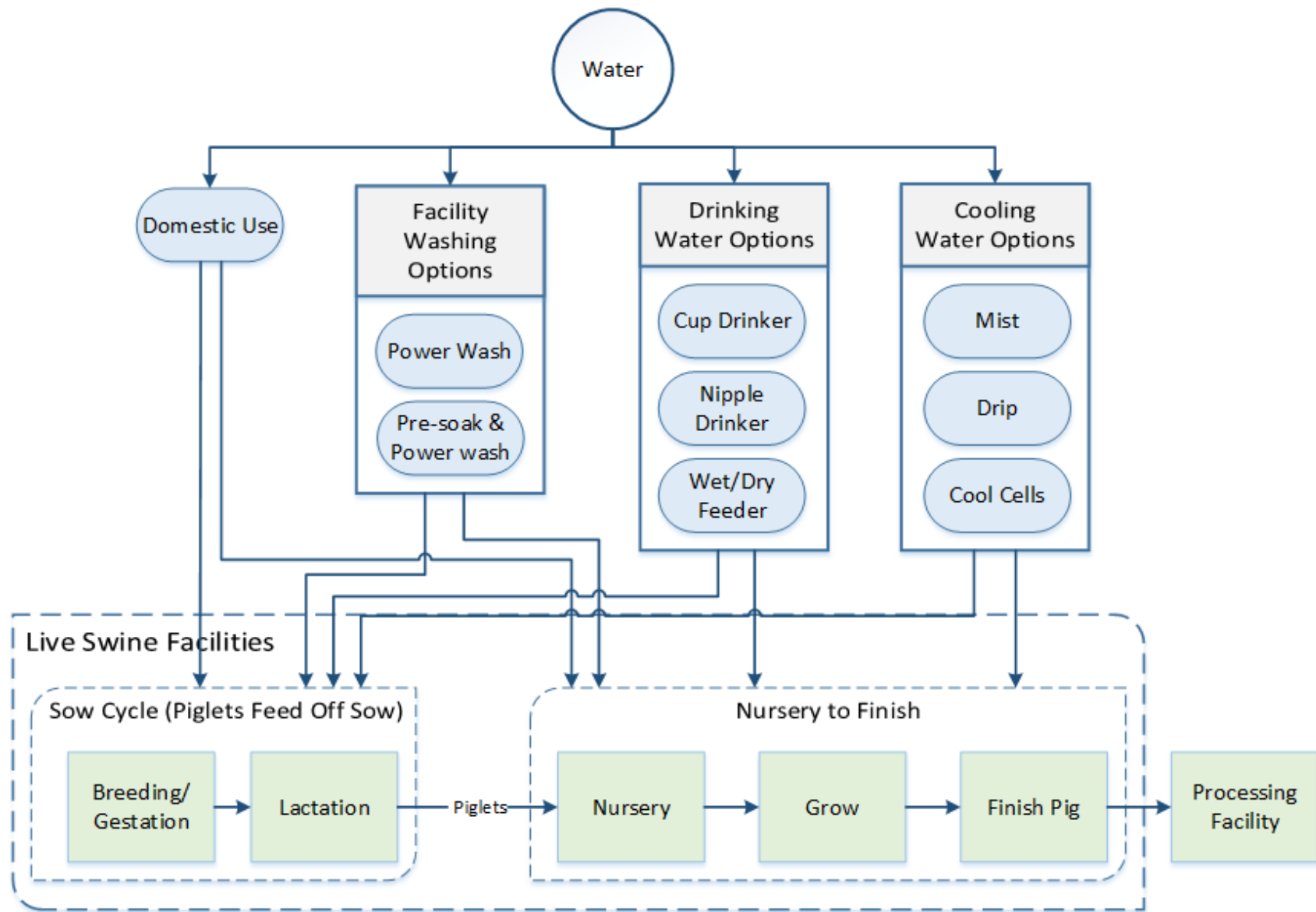


Figure 4. Live swine facility water use diagram.



### 1.2.3. Water Use at the Swine Production Facility

Pork production at a live swine facility is the next step in the supply chain. We defined the system boundaries for a typical production facility as shown in Figure 4. Within the production facility, the system was broken down into different stages including gestation, farrowing, nursery, and finishing. Muhlbauer et al. (2010) reported the percentage of the total facility water consumed in each production stage. They reported that the largest amount of water was used in the finishing phase (64%) followed by gestation (16%), nursery (11%), and farrowing (9%) (Muhlbauer et al., 2010).

Water inputs and the associated delivery technologies were considered for each life phase of pork production (Figure 4). For example, drinking water is consumed in each phase, and drinking water consumption varies depending on which of the water delivery technologies are used. The same was true for facility washing and cooling water. It was important to determine the appropriate volume of water for each phase, region and scale, in addition to the most common dispensing methods for a particular production strategy. The use of drinking water, cooling water, and cleaning water for manure management and transport are discussed in more detail in the following sections.

## 1.3. Drinking Water Consumption in Swine Production Facilities

### 1.3.1. Pig Drinker Systems

Drinking water has been predicted to make up the largest amount of the live swine facility water footprint (Muhlbauer et al., 2010). For this reason, it was important to fully understand drinking water consumption at each life stage. The drinking systems considered here are widely used technologies in the U.S. pork production industry: nipple drinker systems, cup drinking systems, and wet/dry feeders. Nipple drinkers are emphasized in this report as they are the most commonly used system in North American swine production (Patience, 2012).

#### 1.3.1.a Nipple Drinker System

In general, nipple drinkers are water dispensers that do not capture water that is spilled while the animal is drinking. These drinkers provide an outflow of water when pigs place their mouths against a small exposed outlet (Figure 5). Instead of being directed to a collection apparatus, the excess flow is routed into manure storage and is lost from the system (Muhlbauer et al., 2010). As a result of the absence of a water collection vessel in nipple drinker systems, and the tendency of swine to move against the nipples when they are not being used for drinking, nipple drinker systems are associated with the highest wastage rate (Muhlbauer et al., 2010).

However, there are management techniques that are currently in use that can decrease the amount of water lost from nipple systems. By altering the mounted height of the nipple, and the system flow rate, producers have been able to improve the water use efficiency of nipple drinkers. In their comparison of nipple drinker efficiency studies, Muhlbauer et al. (2010) reported that by regularly raising the nipple height to the shoulder level of the swine, and by reducing water flow rates, water wastage can be



*Figure 1. Nipple drinking system  
(Mountainharvestorganic.com, 2011)*

decreased by 15% (Li & Chénard, 2005). The alterations in the drinker systems did not change the daily water intake by the pigs. Commonly used swing nipple-type drinker systems are mounted on the ceiling and are allowed to move freely within the production area. The height of these systems can be easily adjusted to improve water use efficiency. In addition, the swinging nipple systems are displaced when the swine move against them, resulting in an 11% decrease in water waste compared to conventional nipple drinkers (Brumm, 2000).

Other systems use a variation of the nipple drinker known as bite ball style drinkers, which require that the outlet be inserted further in the pig's mouth before water is dispensed, reducing wasted water (Muhlbauer et al., 2010). Li and Chénard (2005) showed that nipple drinkers not regularly raised to the pig's shoulder height with 1000mL/min peak flow rates had the largest wastage (41.8%) compared to shoulder height adjusted drinkers with 500mL/min flow rates (15.1%). Studies of bite ball style drinkers showed reductions in overall water use of 8-22% compared to traditional nipple drinker systems over different growth stages (Muhlbauer et al., 2010). By altering the mounted height of the nipple, and the system flow rate, producers have been able to approach but not reach the efficiency of other drinker systems. To the extent that pig watering is a water use of concern, these technologies could be employed to reduce water use.

#### 1.3.1.b Cup Drinking System

Cup drinkers use a collection basin to provide drinking water. A lever, when moved by a pig, releases water into a basin or bowl that the pig can then drink from. Alternatively, the basin could have a liquid-level float switch to control water delivery.

In general, cup style drinkers have higher water use efficiencies than nipple drinkers. The collection of excess water in a basin minimizes wastage, as all of the water pumped into the system can be used by the pigs, though water is still lost in small volumes due to evaporation and splashing by the pigs in drinking or play. Muhlbauer et al. (2010) cited studies comparing water use in cup and nipple drinker systems, and the reduction in use from the cup drinkers ranged from 20-31.2% in the nursery and finisher phases. A potential problem associated with cup drinkers is the retention of potentially contaminated water in the drinking water basins; however, studies have not identified any impacts on pig performance resulting from changes in drinker type (Muhlbauer et al., 2010).



*Figure 2. Cup drinking system (Gillisag.com, 2010)*

### 1.3.1.c Wet/Dry Feeder

A wet/dry trough mixes feed and water in the same container. These troughs cause a reduction in water consumption per day, with the savings occurring mostly in the growing and finishing stages (Muhlbauer et al., 2010).



*Figure 3. Wet/dry feeder trough (Christianson et al., 2009).*

As with the cup drinkers, the capture of water in the feed basin increases water use efficiency compared to nipple style drinkers. The concerns with wet/dry troughs mirror those of cup drinkers, most notably the retention of contaminated water in the reservoir. Some producers say that pigs find the food less appetizing after it is saturated, causing them to eat less food; however, no changes in gains have been documented between the different drinker types (Muhlbauer et al., 2010).

### 1.3.2. Effects of Temperature on Drinking Water Consumption

The temperature and relative humidity of a pig's surroundings are known to affect the pig's desire to consume food and water (NRC, 2012). Climate can also have non-physiological effects on pigs that impact water consumption. According to Patience (2012), it is common for bored or heat stressed pigs to waste more water while playing with drinkers. As a result, higher ambient temperatures often result in an increase in water use.

However, the overall relationship between swine drinking water use and temperature is not straightforward. From a behavioral perspective, it is unclear which external factors most affect drinking water demand. Ingram & Stephens (1979) evaluated the relative importance of thermal conditions on pig water consumption and concluded that there was insufficient evidence to predict drinking water by manipulating the pigs' thermo-receptors.

In contrast to water consumption, food consumption shows a strong decreasing trend as temperature increases, with a corresponding increase in respiration rates (Renaudeau, 2010). This decline in daily feed consumption is most likely the result of a physiological mechanism that is triggered to reduce the metabolic heat produced by the pig. Increasing respiration is a pig's main physiological pathway to accelerate heat exchange. These phenomena are accounted for in the daily water requirement averages shown in Table 1.

Table 1. Values reported in literature for the average daily water intake of pigs in each life stage.

Pig Life Stage	Drinking System	Average Daily Water Intake (gal/pigspace/day)	Standard Deviation	Min	Max
Gestation <sup>1,2,5,7</sup>	nipple	4.6	1.25	3.5	6.4
Lactation <sup>1,2,5,7</sup>	nipple	6.8	2.2	4.8	9.9
Nursery <sup>1,7,9</sup>	nipple	0.8	0.12	0.7	0.9
Grower <sup>1,5,6,7,8</sup>	nipple	1.5	0.84	1.4	2.1
Finisher <sup>1,3,4,6,8,10</sup>	nipple	2.2	0.94	1.4	4.0

<sup>1</sup>Almond, 1995; <sup>2</sup>Almond, 2002; <sup>3</sup>Amornthewaphat et al., 2000; <sup>4</sup>Brumm, 1999; <sup>5</sup>Brumm, 2006; <sup>6</sup>Christiansen, 2002; <sup>7</sup>Froese & Small, 2001; <sup>8</sup>Li, 2005; <sup>9</sup>Margowen, 2007; <sup>10</sup>Rantanen, 1994

The volume of water each pig consumes will fluctuate (not always predictably) depending on circumstances such as age, temperature, humidity, airspeed, stocking density, drinker flow rate, disease or stress level, and feed composition (Stockill, 1991, Nyachoti, 2001). As a result, most drinking systems have been designed to provide pigs with as much water as they will drink. A downside of this approach is high wastage rates related to water delivery systems, flow rates, barn temperature and pig behavior. Phillips et al. (1989) reported that drinking systems could result in wastage rates of up to 80% in commercial sow barn operations. Li (2005) recorded water waste to be as high as 42% with high flow, unadjusted height nipple drinkers in finishing operations.

### **1.3.3. Sow Drinking Water for Gestation and Lactation**

The sow stage is more water intensive per head than the subsequent production stages, as shown in Table 1. The higher consumption rates require maximum nipple flow rates of 0.26 gal/min (1000 mL/min) for gestating sows and 0.40 gal/min (1500 mL/min) for lactating sows. The high nipple flow rates likely account for the reported water wastage rates of 23-80% (Patience, 2012).

During the farrowing and lactation phase it has been shown that, within a reasonable range, water consumption of the sow does not affect the gain of piglets (Almond, 2002). The lactating sows' daily water intake is the highest of all growth phases and ranged from 4.8-9.9 gal/day (Almond, 1995, Froese & Small 2001). The higher water intake in the lactation phase can be partially attributed to the piglets' nutritional reliance upon the sow. Lactation and gestation have the largest standard deviation of reported drinking water values (Table 1).

### **1.3.4. Nursery Drinking Water Consumption**

Water-to-feed ratios are reported by Patience (2012) for all life cycles other than the nursery phase. Nursery barns do not have consistent correlations between the quantity of water and the quantity of feed consumed. The nursery stage is known to have the lowest drinking water requirements per pig of all the growth stages (Table 1). Lower peak flow rates (0.13 gal/min) (500 mL/min) than other growth stages are recommended for nursery pigs (Patience, 2012).

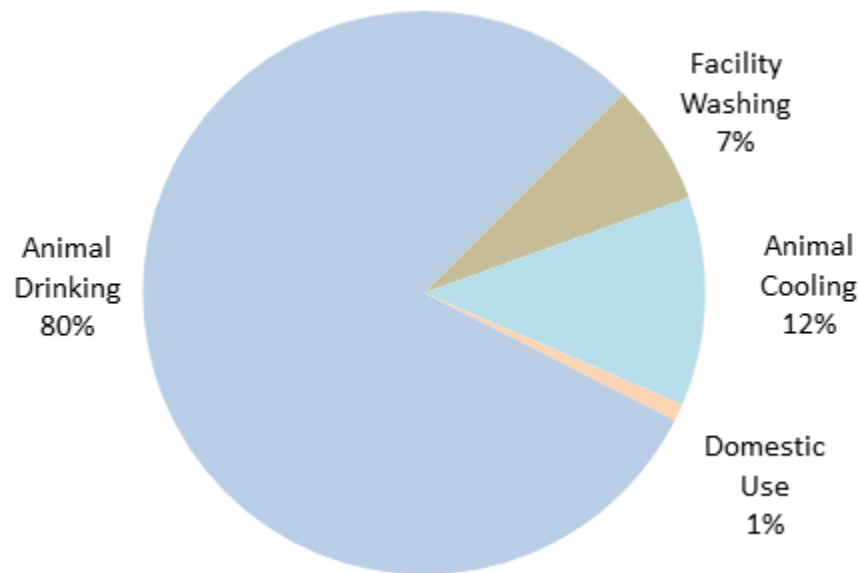
### **1.3.5. Grow-Finish Water Consumption**

Water consumption for growing/finishing pigs mostly occurs immediately before or after feeding with approximately 85% of daily water consumption occurring at that time (Patience, 2012). Pigs will employ extra effort in order to obtain water from lower flow (0.03 gal/min) drinkers,

suggesting that lower flow rates would not significantly affect pig performance (Brumm, 2008). However, Patience (2012) recommends nipple flow rates of 0.20 gal/min (750 mL/min) for growing and finishing pigs.

#### 1.4. Cooling Water Consumption in Swine Production Facilities

After drinking water systems, cooling systems are the second largest consumer of water in live swine production facilities (Figure 8). The influence of cooling technologies, climate, barn type and stocking density on cooling water consumption is discussed in the following sections.



*Figure 8. The average water use breakdown from nine farrow to finish swine operations (excluding feed footprint) from survey data. Adapted from Muhlbauer et al. (2010).*

##### 1.4.1. Cooling Technologies

In warmer climates, depending on the type of barns employed, water may be needed to cool pigs in the gestation, farrowing, and finish phases. It should be noted that nursery barns do not often require cooling since nursery pigs easily tolerate temperatures as high as 90°F (Table 2). Water is usually dispensed onto the pigs using a drip or sprinkling/misting system. Water is also used in evaporative cooling pads (cool cells) that remain wet and evaporatively remove heat from the fresh air being forced through the porous cooling pad with electric fans as it enters a barn. In a

drip or sprinkler cooling system, water is dispersed onto the pigs, and as it evaporates, heat is removed from the animal. With evaporative cooling pads, the air temperature is lowered allowing better heat transfer from the pig to the passing air. All water cooling systems require air flow across the animal. As shown in Table 2, cooling water requirements vary with cooling technology and regional temperature (Muhlbauer et al., 2010).

Table 2. Estimated water use for different swine cooling systems used (Midwest Plan Service, 1991).

Cooling Technology	Recommended water flow rate when above 85°F (gal/pig/hr)
Sprinkler	0.1
Drip	0.75
Evaporative Pad	0.6

#### 1.4.2. Effects of Regional Climate on Cooling Requirements

Where water is used for cooling animals, the quantity required is affected by regional climate and cooling technology, and can vary from 28 gal/pig/year to 258 gal/pig/year. In Table 2, the Midwest Plan Service (1991) has recommended water flow rates for each of the three most common cooling technologies. Relative humidity also affects cooling requirements but its effects are not well quantified in swine literature.

#### 1.4.3. Effects of Barn Infrastructure on Cooling Requirements

The three barn infrastructure types reviewed in this study were drop curtain, tunnel ventilated and hoop barns. Drop curtain barns are often used in warmer climates since they can be naturally ventilated without additional energy input. If supplemental cooling is required, drop curtain barns generally use sprinkler/misting systems. Tunnel ventilated barns, on the other hand, are well suited for the use of evaporative pad cooling, with fans at each end of the barn forcing air across the production area. In warmer climates, some tunnel ventilated barns also have sprinkler systems installed.

The cooling requirements for hoop barns are very similar to drop curtain barns since they also utilize natural ventilation. Some hoop barns may also have sprinkler/misting systems in warm climates, but it is not desirable to wet the natural bedding (corn stalks, straw, wood shavings, etc.). Consequently, hoop barns are often selected for cooler climates where cooling systems are

not as necessary. Hoop barns are built with approximately 50% more space per pig than confinement pigs (Purdue Handbook, 2008), which could decrease the need for cooling in the summer, but increase the need for heating in the winter.

#### **1.4.4. Effects of Stocking Density on Water Consumption**

Pigs add significant heat to their environment when closely confined. Stocking density is defined as the number of animals per floor space. Recommended densities are based on animal size and stage of growth and can have a significant effect on the amount of cooling necessary to keep the pigs healthy.

Research trials have consistently shown that increased stocking density leads to a reduction in feed consumption from nursery to finish with concomitant average daily gain decreases (Kornegay and Notter, 1984; Brumm, 2006). Some researchers have tried to overcome this problem by increasing the nutrient density of the food, but daily gain was still depressed in crowded facilities (Brumm, 2006). Since there are significant water requirements associated with feed production, a reduction in daily feed intake reduces daily water footprint, but that effect is countered by the reduction in daily gain. Turner et al. (1999) documented that pigs will use more water when they are in larger groups than smaller groups, even when the pig per drinker ratio was maintained.

#### **1.4.5. Cooling Requirements by Life Phase**

##### **1.4.5.a Sow Cooling**

Piglets in the farrowing barn with sows prefer a much higher temperature range than sows (Table 3). In fact, piglets are often supplied with heating pads or lamps to provide supplemental warmth. In Table 2 above, sprinkler cooling uses less water than other technologies, but it is not optimal for a sow barn during farrowing since the piglets would also be cooled (MWPS, 1991). When the sow is in a farrowing room, drip cooling can be used to effectively cool only the sow. If supplemental cooling is employed at sow barns it is typically evaporative pads (cool cells).



Table 3. Recommended thermal conditions for each swine production stage (FASS, 2010; Thompson, 1996).

Life stage	Body Weight (lb)	Preferred range (°F)	Lower intervention <sup>1</sup> (°F)	Upper intervention <sup>2</sup> (°F)
Sow	>220	60 – 75	5	90
Lactating sow	>220	60 – 80	60	90
Piglets	< 10	>90	80	100
Pre-nursery	10 – 30	80 – 90	60	95
Nursery	30 – 75	65 – 80	40	95
Growing	75 – 150	60 – 75	25	90
Finishing	150 – 220	50 – 75	50	90

<sup>1</sup>Additional heating in some form needs to be considered when temperatures at the pig near the lower intervention temperature.

<sup>2</sup>Additional cooling in some form needs to be considered when temperatures at the pig near the upper intervention temperature.

<sup>1,2</sup>Without intervention, pig health and growth may be compromised.

#### 1.4.5.b Nursery Cooling

Nursery pigs do not require as much cooling water as older pigs because they prefer warmer temperatures (Table 3). Water-based cooling systems are not usually used for pre-nursery or nursery pigs. In nursery barns, warming is often of greater concern than cooling, depending on the climate.

#### 1.4.5.c Grow-Finish Cooling

Grow-finish barns may use sprinkler/mister cooling, evaporative pad cooling (cool cells) or a combination of the two technologies. The body heat from larger pigs can significantly increase the barn temperature. Larger pigs therefore need more cooling to stay healthy.

### 1.5. Manure Management Systems and Washing Water

Facility washing, which is the third largest source of water consumption in a live swine production facility, accounts for 7% of the water used (Figure 8). In order to maintain a sanitary environment for the pigs, the manure must be removed or flushed from production areas, and the stalls must be cleaned and sanitized. The following sections discuss the types of manure management and cleaning systems currently used in swine production facilities.

### 1.5.1. Types of Manure Management Systems

Manure management varies from operation to operation. In most swine operations, a slatted floor with sub pits collect pig excrement and wasted food and water. In a typical application, the water required to flush and maintain a manure management system is recycled from a previous application or is drawn directly from a storage lagoon. The only additional water consumed in manure management is associated with the cleaning and sanitization of pig space. The water use from cleaning is addressed in Section 1.5.2. Hoop barns make use of dry collection methods. The most common types of sub pits include subfloor to lagoon or formed (above or in-ground) storage structures and deep pits.

#### 1.5.1.a Deep Pit

Deep pit manure management utilizes deep subfloor pits to collect and store manure until removal for land application and does not require additional water. Using data for manure management systems from the EPA (2011) and farm demographics from NASS Census (2007) data, we were able to estimate that deep pits are the most common manure management system and are used in the production of over 40% of the pigs produced in the U.S.

#### 1.5.1.b Subfloor to External Storage System

Subfloor to lagoons or formed storage systems involve the periodic flushing or scraping of subfloor pits into lagoons or formed (above or in-ground) storage structures. Pig manure is excreted in a highly liquid form, and the additional urine along with some drinking water wastage keep subfloor pits in a liquid state. The flushing of a subfloor pit is often initiated by the removal of a sub pit plug and followed by cycling recycled lagoon water through the pit. There are also systems that use shallow below building pits and mechanical scrapers rather than flushing manure with recycled water to the lagoon or storage system. Anaerobic lagoon systems are used in the production of approximately 32% of the pigs produced in the U.S. (NASS Census, 2007, EPA, 2011).

#### 1.5.1.c Dry Cleanup Techniques

Dry cleanup techniques are good for removing solid manure that has collected on shelter or transport vehicle flooring. Generally dry cleanup techniques will be used to remove the bulk of bedding and manure and then a presoak (to soften dried manure) followed by power washing can be used to remove the remainder of residues. The initial dry bedding/manure removal can

significantly reduce the time and subsequently water needed to power wash a barn or transport vehicle.

Hoop barns rely solely on dry cleanup strategies to manage manure between cycles. The manure and bedding is usually removed by a skid loader or tractor bucket and is most often land applied.

### 1.5.2. Factors Affecting Washing Water Use Requirements

It is commonly known that water temperature, presoaking, cleaning agents, water pressure and flow rate all affect washing time and water consumption. A study by Hurnik (2005) compared different washing techniques and concluded that hot water reduced washing times by an average of 22%, presoaking reduced washing time by an average of 50%, and cleaning agents (soap) reduced washing time by an average of 8%. The study did not report actual water consumption, but it is likely that reduced washing times would also reduce water consumption by similar margins. Variation between washing techniques is common, but for this study we adopted the industry average as shown in Table 4.

All-in, all-out facilities, where pigs enter a barn and are sent to market as a cohort at the same time, are increasingly common in the pork industry. Facility washing is much more efficient when the entire facility can be washed between cycles of pigs rather than washing each pig space individually as in a continuous flow barn.

A Veterinary Infectious Diseases Organization (VIDO, 1998) survey of western Canadian swine barns reported a wide range of wash water use due to differences in washing and presoaking practices. Iowa State University conducted a survey (Muhlbauer et al., 2010) of 160 large swine operations that had a smaller range of values than the VIDO study which sampled a larger variety of washing practices. Averages of the values from both surveys are shown in Table 4. Some of the table's cells have been left blank since not all production phases reported in the two surveys pair but do overlap.

*Table 4. Average wash water use by pork production phase from two producer surveys.*

Production phase	Average wash water use VIDO (1998) (gal/pigspace/wash)	Average wash water use (Muhlbauer et al., 2010) (gal/pigspace/wash)
Farrowing <sup>1</sup>	40.1	31.6
Nursery	3.17	–
Wean-Finish	–	7.41
Finishing	21.1	–

<sup>1</sup>Farrowing pigspace was assumed to equal one farrowing crate.

### 1.5.3. Wash Water Requirements by Life Phase

#### 1.5.3.a Sow Barn Washing

Breeding/gestation barns and farrowing barns are less likely to be all-in all-out facilities and therefore require each stall to be cleaned individually when the sow transitions between the gestation barn and farrowing barn. Both gestation barns and farrowing barns are washed about 2.5 times per year if each stall is washed between each sow.

#### 1.5.3.b Nursery Barn Washing

Nursery barns have a much higher turnover than sow and finishing barns; therefore, the nursery barns get washed about 6 times per year-with each new cycle of nursery pigs. The wash water per pig space is less than grow and sow barns, but the ratio of floor space to wash water is consistent, as the space per pig is smaller.

### 1.5.4. Pig Transportation Vehicle Wash Water Requirements

Another consideration for water use is cleaning the vehicles used to transport live animals. Pig transportation systems require proper cleaning agents and techniques to minimize the spread of disease. Generally, swine transport trucks are washed after every load. The current biosecurity practice requires cleaning of all swine related vehicles (including veterinary and maintenance vehicles). Each of these vehicles must be cleaned and care taken to ensure the biosecurity of each facility, including gilt development sites, and gestation/farrowing sites.

In an Iowa State University survey, Muhlbauer et al. (2010) observed that to clean the average 185-200 pig capacity transport vehicle required 750 gallons per truck for delivery of the finished hogs. A system that relied partially on scraping and shoveling in addition to recycling other waste water would reduce water use. However, in order to maintain biosecurity it is necessary to continue using fresh water for final disinfection.

The transportation wash station can be physically located either on or off the swine farm. In our analysis, the live swine transport water use was not assigned to the swine farm operation. It was accounted as an independent unit operation occurring between the live swine facility and the processing plant.

## **1.6. Wasted Water**

There are various technologies which could be used to reduce total water usage by up to 50% in some swine production operations (Froese, 2001). The largest water reductions could come from the implementation of water-saving drinking equipment like trough or cup drinkers. Other practices like soaking before power washing, setting appropriate drinker heights, and implementing proper cooling system management can lead to increased water savings without additional cost. Beyond the typical amounts of water use and waste, improper installation and poor design can lead to annual wastage of water that is largely avoidable. Most of this can be managed by simple, routine maintenance.

## **1.7. Current Gaps in Knowledge**

Since crop production contributes the largest percentage of the pork water footprint, there is a critical need for spatially explicit LCAs to be established on all feed inputs. The advent of the 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 lack of a uniform and consistent feed formulation reporting system across the pork industry presents a significant challenge when trying to determine the composition and origin of feeds. Knowing the specific provenance of feed ingredients is critical for estimating an accurate water footprint for the ration. For example, corn could be heavily irrigated in western Nebraska (large footprint) while only sparsely irrigated in eastern Nebraska (small footprint). Higher resolution feed production LCAs and knowledge of the feed provenance for specific operations will increase the accuracy of animal product footprints.

Additionally, there is a need for detailed pig growth and performance algorithms that accurately account for the synergistic effects of barn design, temperature, humidity, airspeed, stocking

density, drinker flow rate, drinker style, disease, and feed composition. There is research that addresses many of these treatments individually, but more research is needed before accurate algorithms can be developed to account for complex interactions between treatments. In other words, removing cooling systems from a barn would reduce the barn's water consumption, but the negative effects on pig performance could easily outweigh the water saved, while proper ventilation could allow for all the cooling needed in some climates. That is a very simple example of the many complex interactions and concerns that a pork producer is faced with. At this time, there are easily implementable management practices that could lead to significant water reduction, and should be considered on a case-by-case basis.

## Chapter 2. Scan-Level Life Cycle Assessment

### 2.1. Introduction

The goal of this study was to analyze water usage in the U.S. pork industry using life cycle assessment (LCA) methodology. LCAs are quantitative analyses of complex systems for the evaluation of the impacts and risks associated with the production system. LCA can be an effective tool for determining comparative advantages of management strategies across specific environmental impacts of concern. The work on this project was divided into the following tasks:

Task A. Literature Review for Water Footprints

Task B. Pork Supply Chain Scan-Level LCA of Water Use

Task C. Live Swine Production Detailed LCA of Water Use

Task D. Pig Production Environmental Footprint Calculator (PPEFC)

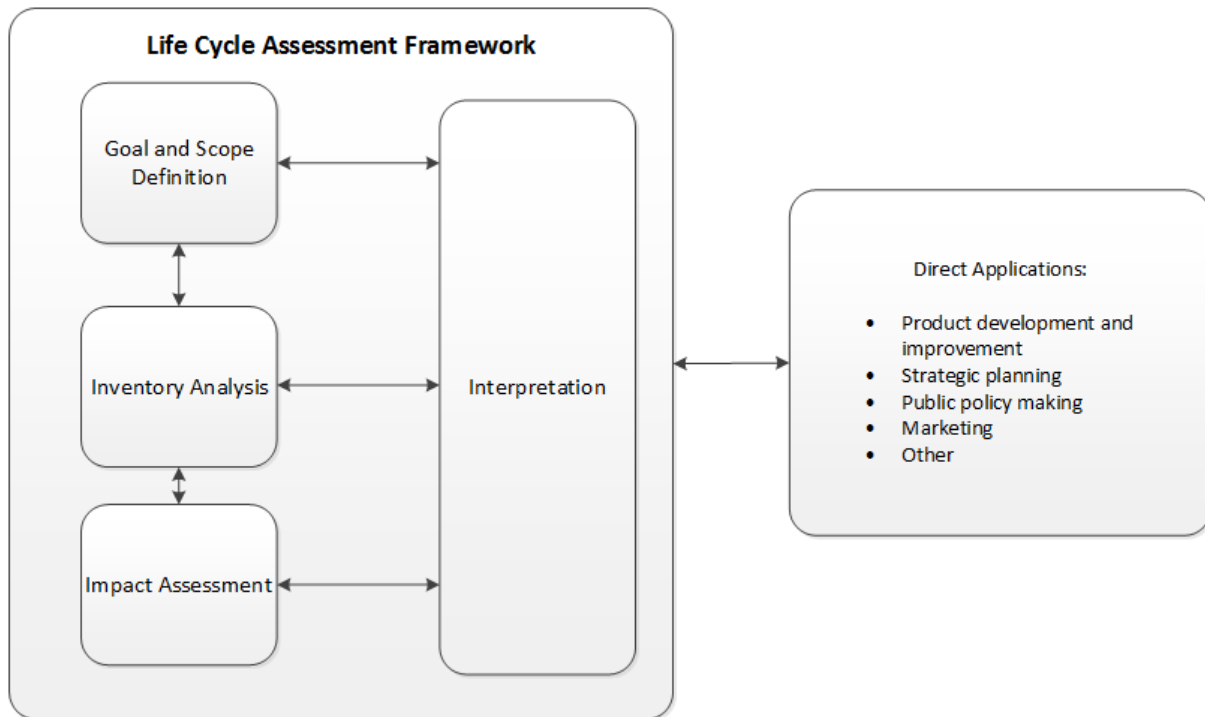
This sub-report presents the results of the scan-level LCA (Task B). The intended audience is the pork industry (growers, processors, packaging companies and retailers) in order to inform internal decision making for increasing the efficiency, profitability, safety and security of the U.S. pork supply chain. This LCA is a cradle-to-grave, scan-level water footprint analysis of the production, distribution, and consumption of U.S. pork.

### 2.2. The Life Cycle Assessment Method

There are currently two methods for analyzing the water footprints of supply chains: The Water Footprint Network (WFN) method and the LCA method for Water Footprints described in the main body of this report. The authors feel that the LCA method provides greater resolution and is more appropriate for this analysis of the U.S. pork industry. The LCA method consists of four iterative stages as follows (see Figure 9).

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

3. Perform an impact assessment
4. Analyze and interpret results



*Figure 4. Stages of a Life Cycle Assessment (LCA)*

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

The Life Cycle Inventory (LCI) phase takes an inventory of all the input/output material and energy flows with regard to the system being studied. During this phase, all water, energy, materials and environmental releases (e.g. air emissions, solid wastes, wastewater discharge) are identified and quantified for each stage of the life cycle.



The life cycle impact assessment phase (LCIA) is the third phase of the LCA. This step calculates the human and ecological effects of material consumption and environmental releases identified during the inventory analysis. For this study, water use was analyzed and reported for U.S. pork production. Life cycle interpretation is the final phase of the LCA procedure, in which the results are summarized and discussed. Its goal is to identify the most significant environmental impacts and the associated life cycle stage, and highlight opportunities for potential improvement or innovation. It should be noted that a full LCA includes multiple environmental indicators, and that decisions based on a single metric, such as water use, frequently result in unintended consequences arising from trade-offs that are not highlighted by the single metric approach.

### **2.2.1. Functional Unit**

The functional unit for this scan-level LCA was defined as a four ounce serving of undefined boneless pork prepared for and consumed by a U.S. consumer.

### **2.2.2. System Boundary**

This life cycle assessment was a field (crop production for feed) to fork (consumption at the consumer's home) analysis of the water footprint of pork. The system boundary includes the environmental impacts associated with feed production, live animal production, and delivery to processor, processing, packaging, distribution, retail, and consumption/disposal. Effects embodied in infrastructure (e.g., water emissions associated with manufacture of new equipment necessary for a new packaging line at a processing facility, which would be amortized over the expected life of the equipment) were not included in the analysis. Water consumption for management of the boar herd were not considered since boar to sow ratios are nearly 1:50 and each sow produces roughly 25 piglets per year, which would make for an annual boar to market hog ratio of 1:1250, and would fall below the 1% contribution threshold. Where data were incomplete, proxy unit operations were identified.

## 2.3. Model Development and Data

Our computational approach was to integrate the Pig Production Environmental Footprint Calculator (PPEFC) developed at the University of Arkansas with an LCA software platform (SimaPro V7.3 Pre' Consultants) to determine the water footprints. The PPEFC was used to generate the scenario LCI inputs which were then linked to SimaPro for the water footprint assessment. Baseline scenarios for the sow, nursery and grow barns for each region were mainly derived from an LCA on pork production management (Thoma et al., 2013). We used the life cycle inventory from the National Life Cycle Carbon Footprint Study for Production of U.S. Swine (Thoma et al. 2011) as the foundation for the LCI model of the supply chain.

### 2.3.1. Pig Production Environmental Footprint Calculator (PPEFC)

The PPEFC uses mathematical relationships to simulate growth, feed intake and water consumption, electricity and natural gas use, manure handling, and greenhouse gas emissions during each production cycle. Separate models were created for the sow, nursery and grow-finish barns. Depending on model input parameters, the grow barn model can simulate nursery, feeder-to-finish, or wean-to-finish barns.

### 2.3.2. SimaPro LCA Model

The SimaPro software platform was used for generating the comprehensive water footprint for each scenario. Data obtained from the literature review was used to create all of the input files and water algorithms for the PPEFC. Next, aspects of the PPEFC output were used in a life cycle inventory for the life cycle analysis model developed in SimaPro V7.3 (Pre' Consultants, The Netherlands). The two models were used in series to produce cradle-to-grave water footprints for 20 scan level scenarios (Figure 10).

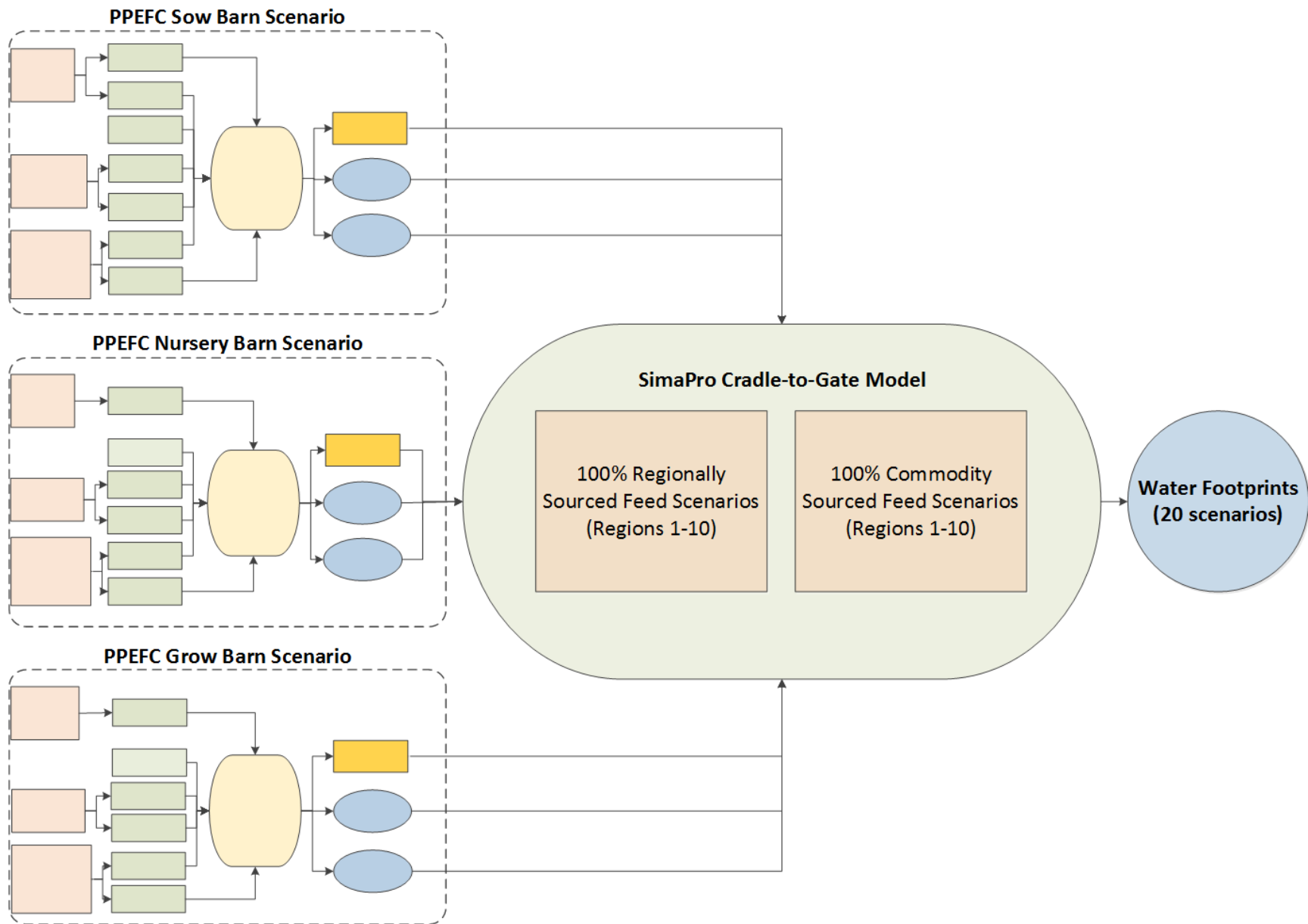


Figure 5. Network diagram showing the links between the Pig Production Footprint Model and the SimaPro model.

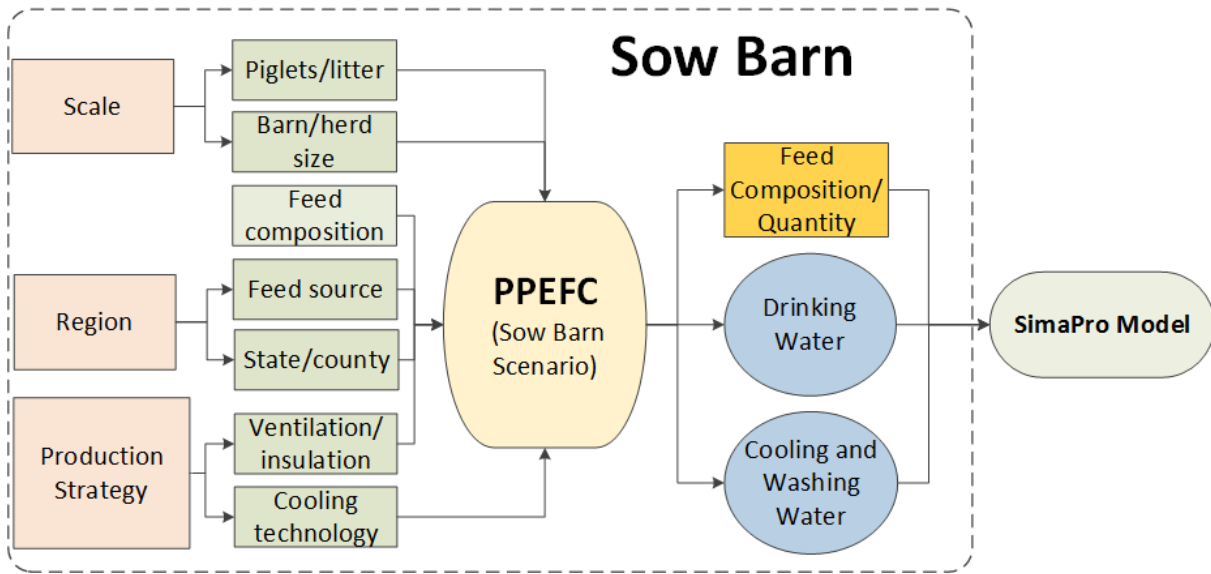


Figure 6. Sow barn Pig Production Environmental Footprint Calculator scenario in detail.

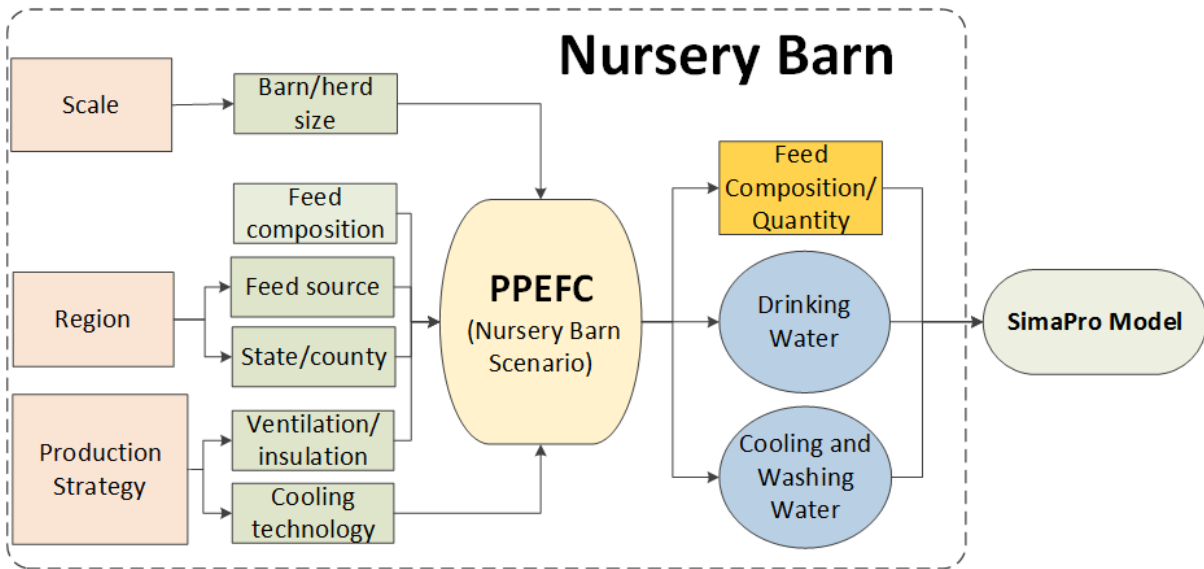


Figure 7. Nursery barn Pig Production Environmental Footprint Calculator scenario in detail.

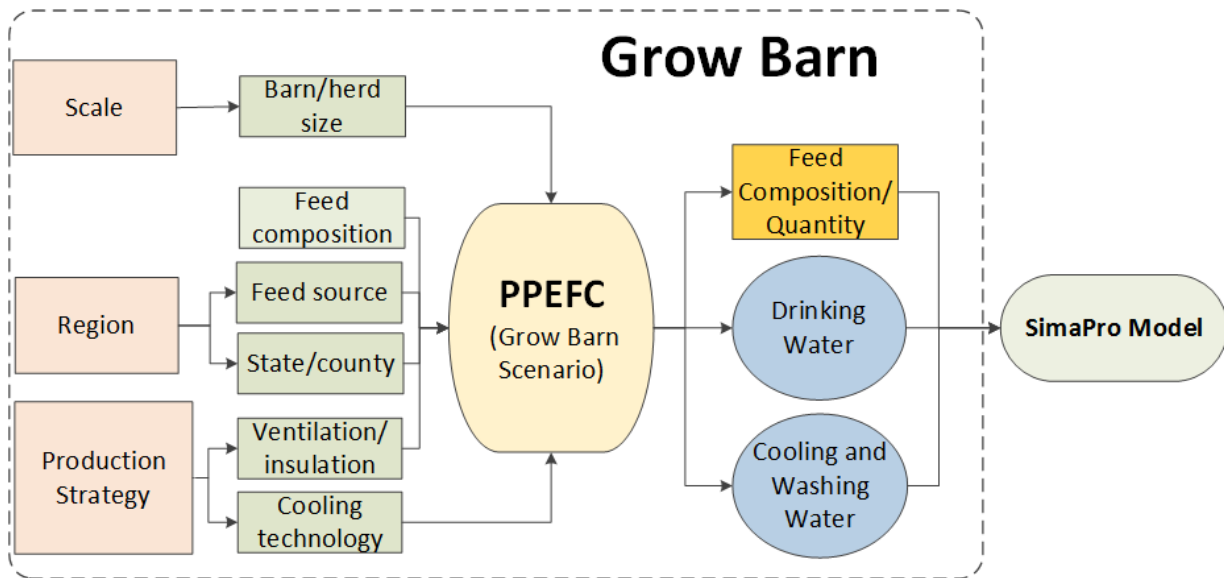


Figure 8. Grow barn Pig Production Environmental Footprint Calculator scenario in detail.

### 2.3.3. Allocation of Co-Products

In LCAs involving systems with multiple products or co-products with economic value, it is necessary to allocate a fraction of the environmental burden of production to each co-product (ISO, 2006). However, in practice, it can be difficult to determine the most appropriate scheme for allocating environmental impacts. The International Organization for Standardization recommends system separation as the highest allocation priority. In cases of co-production, when production of products cannot be independently varied, system expansion takes priority. In system expansion, a “credit” is applied to the system for the production of each co-product that is equivalent to other products on the market. The credit is based on the amount of environmental burden associated with the equivalent products. Other approaches include mass and economic allocation. Mass-based allocation involves applying the weight ratios associated with co-products to their impacts, while economic allocation is based on the relative revenue of each of the co-products (Thoma et al., 2011).

## 2.4. Life Cycle Inventory

The literature review conducted in Task A, Ecoinvent unit processes, correspondence with industry experts, and the previously conducted Pork Carbon Footprint LCA (Thoma et al., 2011) served as the basis for much of the life cycle inventory data which was generated through the PPEFC. The production system encompassed activities performed in support of pork production,

delivery, processing, retail, consumer use and disposal. The system included water use during processing, packaging and disinfecting. We also included the impacts of distribution and refrigeration. The PPEFC was used to simulate three separate barns: the nursery and grow barns (Table 5) and the sow barn (Table 6).

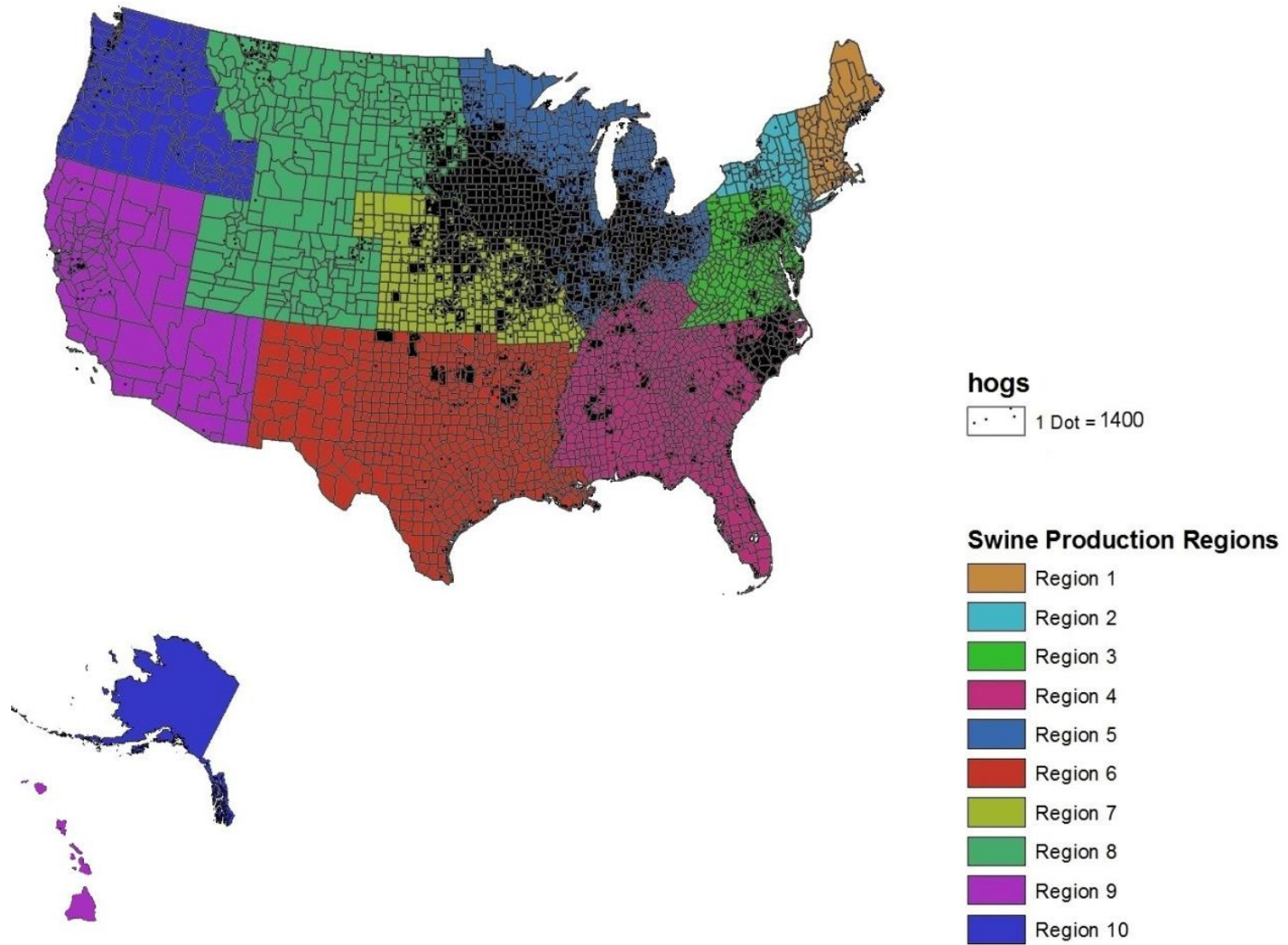
*Table 5. Nursery and grow barn parameters for assessing the scan-level water footprint of U.S. pork production*

Parameter	Nursery	Grow/Finish	Units
Barn infrastructure	Tunnel Ventilated	Tunnel Ventilated	NA
Pigs in per cycle	1200	1200	pig/cycle
Age entering	19	54	days
Weight entering	11	50.1	lbs
Weight leaving	50	275	lbs
Pig death per cycle	35	47	pig/cycle
Mortality	2.9	3.9	%
Mortality disposal method	Composting	Composting	NA
Time to clean between cycles	5	5	days
Barn area	3600	11375	ft <sup>2</sup>
Heat source	Natural Gas	Natural Gas	NA
Outside temp to activate cooling cells	85	80	F
Outside temp to activate sprinkler	no sprinkler	85	F
Sprinkler cooling water	no sprinkler	0.1	gal/pigspace/hr
Manure system	Deep Pit	Deep Pit	NA
Drinking water	0.93	1.87	gal/pig/day
Washing water	3.17	7.41	gal/pigspace/wash

*Table 6. Sow barn parameters for assessing the scan-level water footprint of U.S. pork production.*

Parameter	Sow Barn	Units
Barn infrastructure	Tunnel Ventilated	NA
Adult sows	1200	pigs
Gilts	660	gilts/year
Avg. age gilt	180	days
Culled sows	600	sows/year
Sow deaths	60	pigs/year
Mortality	3.9	%
Disposal method	Composting	NA
Piglets per liter after weaning	9.3	piglets/liter
Death per liter before weaning	2	piglets/liter
Age piglets removed	21	days
Piglet cycle	16	days
Barn area	26500	ft <sup>2</sup>
Heat source	Natural Gas	NA
Heating pads run for	5	days
Outside temp to activate cooling cells	85	F
Outside temp to activate drip cooling	80	F
Drip cooling water	0.77	gal/pigspace/hr
Manure system	Deep Pit	NA
Drinking water	6.4	gal/pig/day
Washing water	31.6	gal/pigspace/wash

The USDA has defined 10 swine production regions in the US, which vary in climate and management practices. We chose these regions as the basis for constructing scenarios for analysis. In order to make use of the historical climate data within the PPEFC, ten archetypal counties were selected to represent the ten regions. The selected counties were obtained by geospatially overlaying the 2007 USDA NASS hog and pig inventory map onto the production region boundaries and choosing counties that would represent the average swine production within the region (Table 7; Figure 14).



*Figure 14. Regions for Analysis with USDA NASS 2007 census statistics overlaid.*



Table 7. Archetypal swine production regions.

Region	Total Head (1000)	Archetypal Climate Region	
		State	County
1	23.69	M	Hampshire
2	193.54	NY	Cayuga
3	2,335.23	PA	Perry
4	14,911.60	NC	Wake
5	32,800.18	IN	Jasper
6	5,620.67	OK	Texas
7	44,277.36	IA	Hardin
8	4,349.36	SD	Edmunds
9	238.00	CA	Stanislaus
10	94.24	OR	Clackamas

#### 2.4.1. Water Use for Crop Production

Water use for crop production was estimated for each of the ten regions (regional footprints) and for the entire U.S. (commodity footprint). It was assumed that the feed crops were produced in the continental United States and standard U.S. agricultural practices were used in their production. Two main sources of agricultural data were used to estimate regional blue water usage in the production of corn grain, soybeans, and wheat in 2007: crop production data from the 2007 Census of Agriculture on a state-by-state basis from the USDA National Agricultural Statistics Service (NASS), and the 2008 USDA NASS Farm and Ranch Irrigation Survey (FRIS). State-level data for acres harvested and average yield for irrigated and non-irrigated acres were obtained from the USDA NASS 2007 Census of Agriculture. The average irrigation amount applied (acre-feet) for irrigated production for each state was obtained from the USDA NASS 2008 Farm and Ranch Irrigation Survey (FRIS). Total irrigation water use and total harvest mass was calculated from these values. Because at the commodity level, it is not known with certainty whether the corn was irrigated or not, the total irrigation water use was divided by total harvest mass to obtain a volume of water use per mass of harvest. These values were aggregated for each region. Missing yield data from the 2007 Census was supplemented using yield data from the 2008 FRIS. Missing irrigation data for states in the 2008 FRIS were supplemented using regional averages. Using the same data, a single commodity feed footprint that could be applied the entire U.S. was compiled using weighted averages. Scenarios were created for all ten regions with both their respective regional feed footprint and the U.S.

commodity feed footprint. It must be noted that in the 100% regional footprints we assumed that pigs in a region were fed feed from crops that were grown in that particular region.

#### **2.4.2. Water Embodied in Rations**

Feed crop life cycle inventories were adapted from the Pork Management LCA (Thoma et al., 2012) base scenario, with the same feed compositions but with additional detail regarding water use in crop production and an updated economic allocation for dry distiller grains (DDGs), a byproduct of corn ethanol production. Data available from the Agricultural Marketing Center (2014) was used to determine five year average prices per mass of ethanol versus distiller's grain and combined with an average production of ethanol versus distiller's grain to determine an average allocation of 19.7% to distiller's grain. Feed compositions were applied uniformly across all production strategies, regions and scales, to avoid confounding changes in the ration with other management practices. The feed compositions are not assumed to be correct for all scenarios, but clearly documented differences between regional feed compositions are not available. Thus, use of region-specific rations would introduce additional uncertainty that would not facilitate well informed decision making.

When feed ingredients were not available in the SimaPro Ecoinvent database, proxy unit operations were substituted. An example of this was a whey unit process was substituted for a nonexistent lactose unit process in the nursery feed. Lactose only attributes 0.1% of the nursery feed composition by weight, so using a quality proxy unit operation did not have a significant impact on water consumption. All of the proxy datasets used for feed ingredients represent less than 2% of the feed compositions by weight and are estimated to have very similar water consumption. As more LCAs become available, they will provide a more thorough foundation for other LCAs to be built upon.

The relationship between pig water consumption and environmental conditions and housing is not well enough established to accurately predict these effects. In this LCA, animal performance and water requirement algorithms were assumed to be the same across all scenarios.

#### **2.4.3. Post Farm Gate Water Use**

Once hogs reach market weight, they are shipped to processing facilities. The water impacts of boutique processors were not considered because of the high variability between operations and uncertainty regarding infrastructure and scales. Due to the proprietary nature of economic data at the retailer, we used shelf space and sales to estimate an appropriate allocation of retail and in-home water use. Ecoinvent unit processes were used to determine upstream water use associated with energy consumption including transportation. The water use associated with energy production is so small that it often falls below the 1% cutoff of the total water footprint, but it was added because it is readily available in the background datasets from Ecoinvent.

#### **2.4.4. Animal Transport to Processor**

Water is used for washing the vehicles used to transport live animals from the farm to the processing facilities. It was assumed these vehicles are washed after every load of pigs. We used an estimate of 3.9gal/head for truck washing water. These calculations are based on an average of 185 to 200 head and 750 gallons per truck for delivery of the finished hogs from a producer survey (Muhlbauer et al., 2010).

#### **2.4.5. Abattoir/Packaging**

In the Scan Level Pork Carbon Footprint Report, Thoma et al. (2011) obtained packaging data from over 10 processing facilities. The study aggregated confidential information on facility water consumption and the total production of processed meat. Thoma et al. (2011) used an economic allocation based on U.S. census data to determine the burden associated with individual co-products. Within the abattoir/packaging unit process, It was determined that 89% of the water burden was associated with the meat processing operations, while 11% was associated with co-products from the rendering operations. The Ecoinvent database contains unit operations that accounted for the water burdens associated with producing the various packaging materials (i.e. polystyrene plates, absorbent pads, and thin plastic film).

#### **2.4.6. Distribution**

Transportation of packaged pork in a refrigerated truck to a retail outlet consumes a very small amount of water, and was accounted for in Thoma et al. (2011). There was little literature regarding additional water use for this step in the pork supply chain.

#### **2.4.7. Retail Outlet**

After transportation from the processor to the retail facility, pork is placed on display for consumer purchase. During this phase, retail store water use was allocated to the pork using methods similar to Thoma et al. (2011). Estimates of space occupied by pork were used to determine the burden at this stage in the supply chain. Thoma et al. (2011) reported that in a typical grocery store configuration, pork products occupy 1.32% of total refrigerated store shelving and 0.26% of total shelving space throughout the store. Those values allowed us to apply a space-occupied allocation to the upstream embodied water usage for an entire retail facility. An average retail loss of pork was assumed to be 4.4%, based on a study by Buzby et al. (2009) on supermarket loss estimates for perishables.

#### 2.4.8. Consumption and Disposal

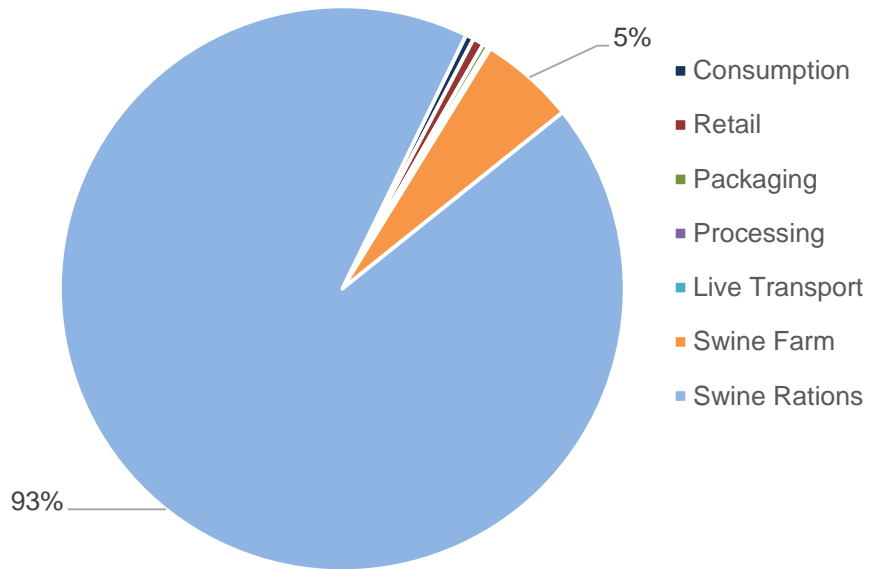
Water accounted for in this phase included transport from the retailer to the home, product refrigeration, cooking and dish washing. Processes such as transportation, refrigeration and cooking have negligible contributions to the water footprint from the upstream fuel and energy production, but were readily available from a U.S. Pork Carbon Footprint study (Thoma et al., 2011). Dish washing has the most significant water use within the consumer phase. A Google image search for dinner plates with 4 ounce servings of pork showed that approximately 30% of the plate area was occupied by pork. Accordingly, only 30% of the water used to wash dinner plates and utensils was allocated to pork, while 100% of the serving plate and serving utensil washing water was allocated to pork. Therefore, 4.4% of the water to operate a single cycle of a typical dishwasher was allocated to one pound of pork, since four servings (4 ounces each) of pork requires approximately 10% of an average dish washers space (10 utensils, 4 dinner plates and 1 serving plate). As in Thoma et al. (2011) we estimated that consumers wasted approximately 10% of edible pork.

### 2.5. Results and Discussion

Overall, the U.S. pork water footprint was estimated to be 8.2 gal/4oz (0.031 m<sup>3</sup>/4oz) serving of boneless pork with a total pork industry water use of 525,000,000,000 gal/yr (1,990,000,000 m<sup>3</sup>/yr) when analyzed using a weighted ration (that is based on a nationally weighted crop production) (Table 8). Figure 15 shows the percent contribution of each life cycle stage to the total water footprint using regional- and commodity-sourced feed. As part of the sensitivity/scenario analysis, all ten of the scenarios were analyzed twice; once with the commodity swine rations and once with regionally sourced rations (Figure 16). In addition, for each region, a weighted ration footprint was calculated using estimated contributions of commodity and regional feed consumption by region (Table 8, Figure 18).

The ration source is very important since feed rations accounted for the greatest cumulative water use, totaling 83% to 93% of the total water footprint, respectively for the commodity and regionally sourced rations. The second largest contributor to the total water footprint was on-farm activities with 5% to 13%, while post-farm-gate activities contributed 2% to 4% of the total water footprint. As expected, we observed considerable variation in the swine ration water use and, consequently, the total water footprint when feed sourced from within a particular region was used (100% regional feed) rather than a nationally weighted average feed source (100% commodity feed) (Figure 16). The transition from a regional feed source to a commodity feed source only affected the contribution from the swine rations.

A. Using 100% Regional Feed



B. Using 100% Commodity Feed

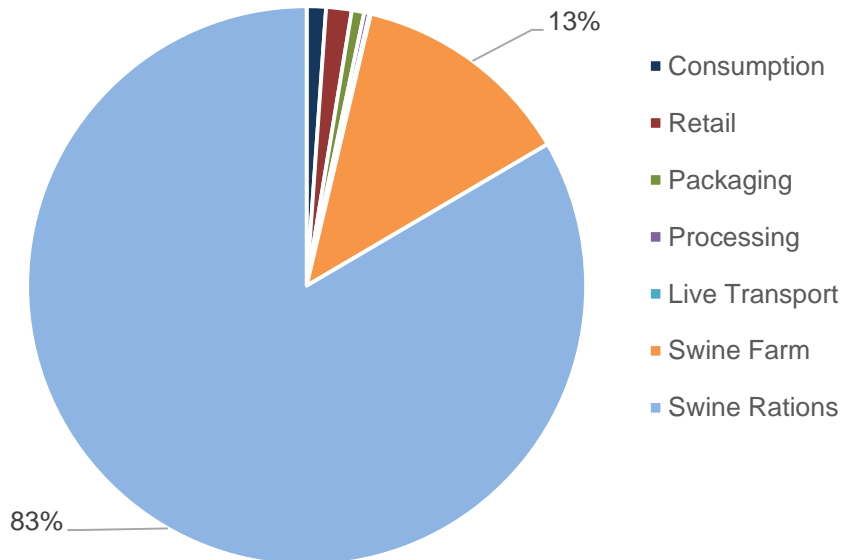


Figure 15. Percentage of total water use associated with each phase of the U.S. pork industry using a.) 100% regionally sourced feed and b.) 100% commoditized feed.

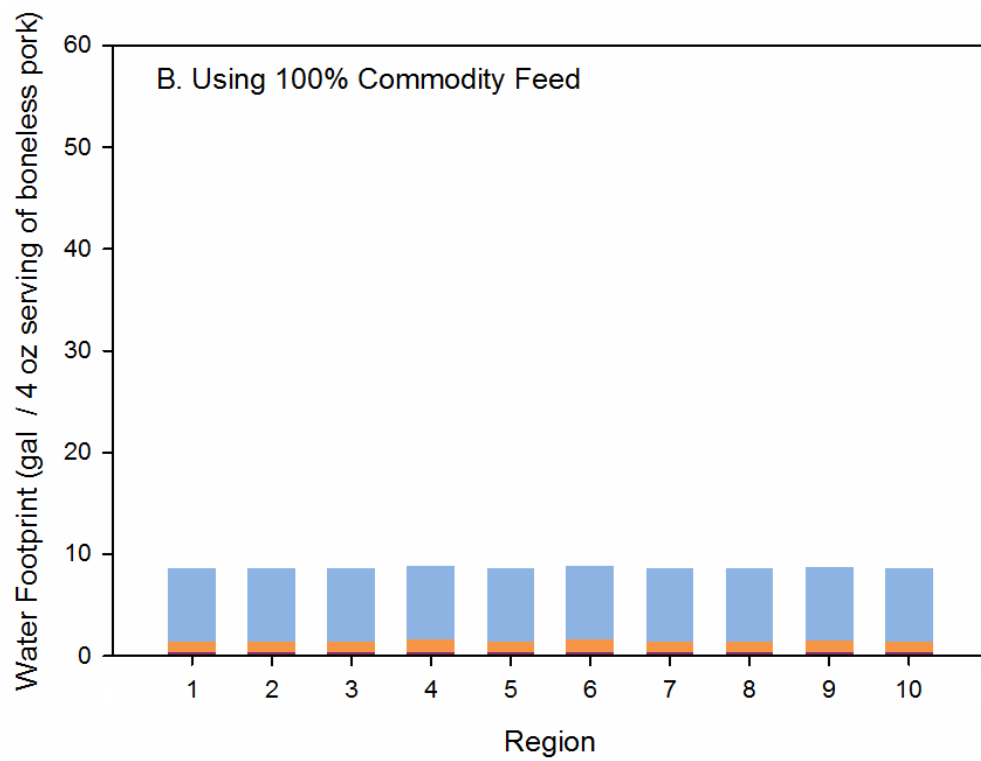
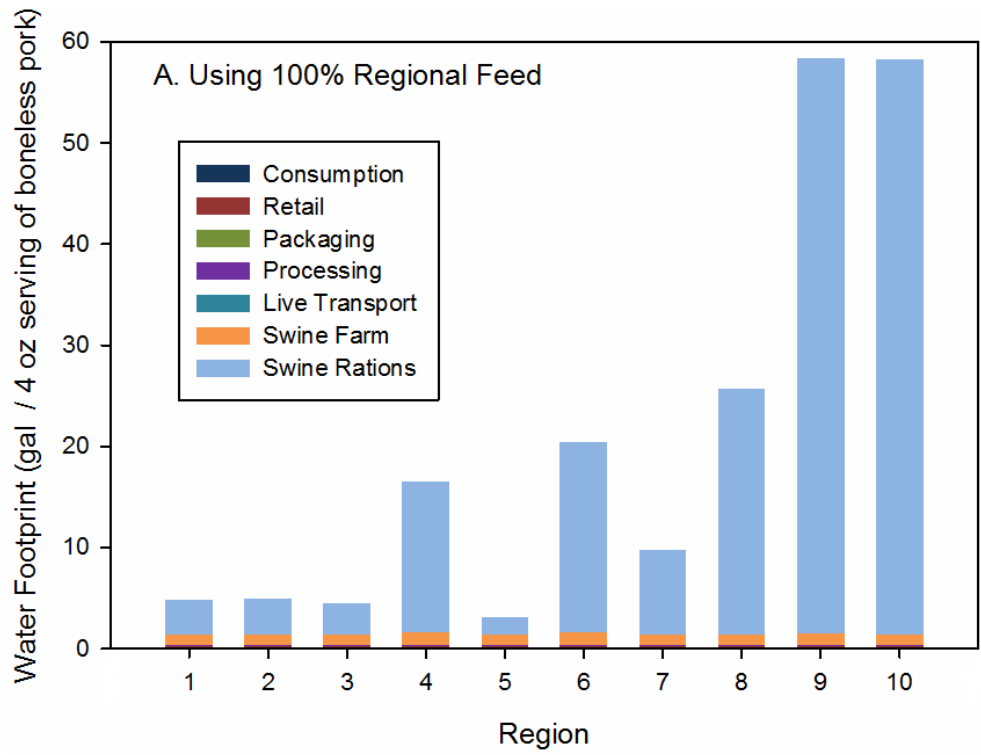


Figure 16. Scan-level water use associated with the consumption of a 4oz. serving of pork when using a.) 100% regional and b.) 100% commodity feed sources. Only the “swine farm” and “swine ration” are easily visible because the other production stages represent a relatively small percentage of the footprints.

The 100% commodity and 100% regionally sourced feed scenarios established the importance of the feed's origin, since the water footprint is very sensitive to the feed source. While these scenarios are useful 'bookends' to the actual situation, in reality supply chains are very dynamic and pork producer's source feeds from various regions of production. The commodity feed composition encompasses much of that complexity, but not in regions that produce a significant quantity of grain. Transportation costs likely induce producers to source more feed from local farms.

In an effort to bring our analysis closer to reality, we estimated the proportion of commodity feed to regionally sourced feed in all 10 regions (see Table 8, Figures 17 and 18). The previous two feed scenarios were essentially the two ends of the spectrum with 100% commodity or 100% regionally sourced feed. The third and final scenario is an estimated ration with a blend of regionally and commodity sourced feeds. It should be noted that some of the regions in Table 8 were estimated to source 100% of their feed from commodity feed or regional feed while other regions were proportioned. For example, Region 1 has essentially no corn or soybean production for feed (NASS, 2007), therefore we assumed producers in Region 1 would exclusively use a commoditized feed blend. The resulting water footprint for Region 1 in Figure 18 is exactly the same as the Region 1 footprint in Figure 16B.

Figure 18 is essentially Figure 17 multiplied out by the number of head in each region. One issue with this exercise is that the post farm gate supply chain has been inaccurately assigned to each region. The post farm gate supply chain should be spread evenly amongst the regions, but in this case it represents such a small portion of each region's footprint that it is insignificant.

*Table 8. Assumed values used in Figures 17 and 18 for the proportion of commodity and regionally sourced feed by region for the weighted ration scenarios. Values were based on NASS (2007) data for corn and soybean production in each region.*

Region	Corn Production <sup>1</sup>	Soybean Production <sup>1</sup>	Commodity Sourced Feed <sup>2</sup>	Regionally Sourced Feed <sup>2</sup>
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%

<sup>1</sup>Corn and soy produced by region as a percentage of total U.S. production in 2007 (NASS, 2007)

<sup>2</sup>Ratios between commodity and regionally sourced feed were estimated by the research team based on the amounts of corn and soybean production in each region



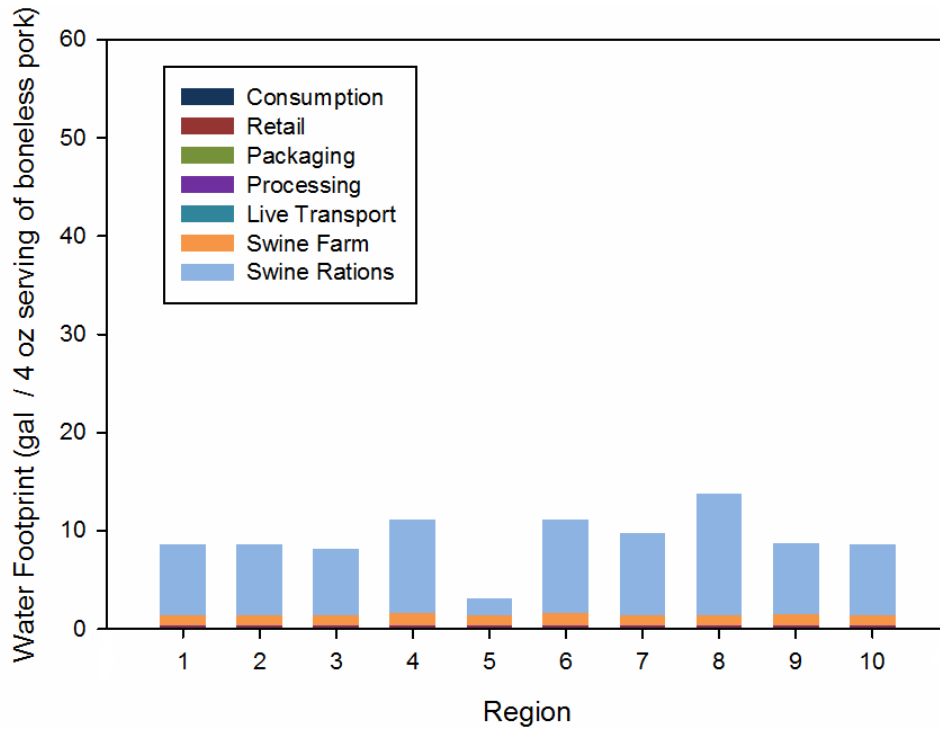


Figure 17. Estimated water use per serving for pork production in each U.S. region using feed sources weighted by the amounts of commodity and regionally sourced feed in the region (see Table 8).

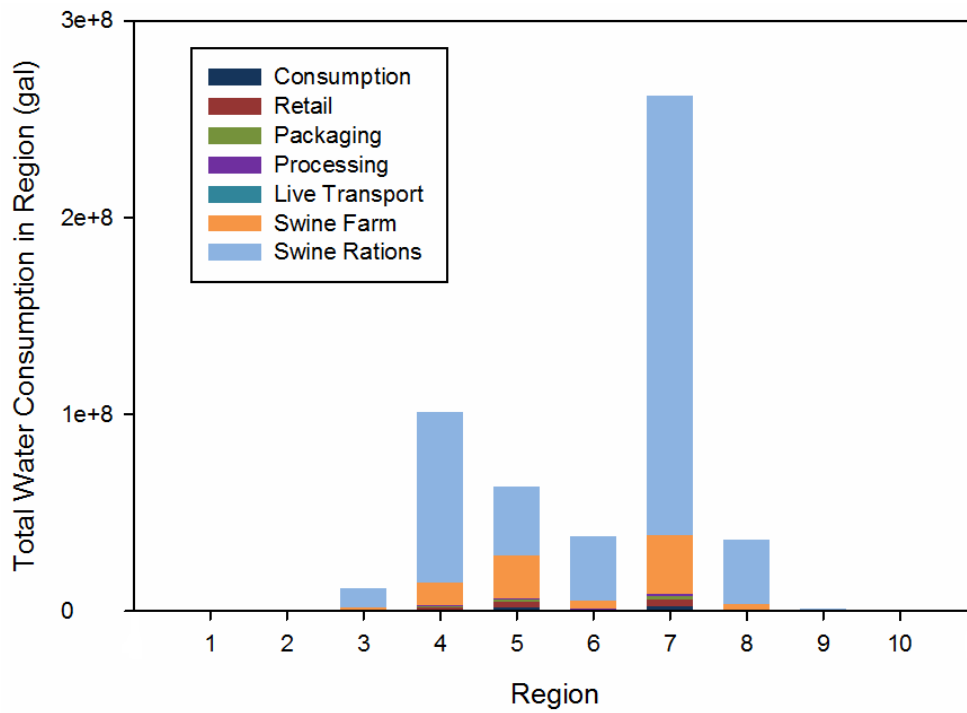


Figure 18. Estimated with pork production in each U.S. region when using feed sources weighted by the amounts of commodity and regionally sourced feed.

The cradle to grave analysis of the water footprint for each phase of pork production for a 4oz serving of pork showed varied impacts across the regions and production phases (Figure 16). Since the feed rations are the single most important contributor to the water footprint, it follows that the source of the feed plays a major role in the total water footprint. The on-farm water footprint varied slightly from region to region due to differences in climate and its effect on the cooling and heating of the barns. In Figure 16 Part B, all of the swine ration footprints were the same, since pigs from all regions were assumed to be fed the same commodity feed, which resulted in a uniform water footprint from the rations. The post-farm-gate supply chain is not affected by changes in region or feed source, and remained constant throughout all 20 scenarios.

The water footprints calculated when using regionally sourced feed were greater in all the regions except for Regions 1, 2, 3, and 5 (Figure 16). Regions 9 and 10 had the largest water footprint from feed, which is likely due to crop production in relatively arid regions that require significantly more irrigation (blue water). These data suggest pork producers in Region 9 and 10 could have lower water footprints if commodity feed were used rather than regional feed. Similarly, producers in Region 5 could achieve lower water footprints if using feed sources from within the respective regions.

Figure 18 and 17 show the total water footprint per serving and cumulative water footprint when weighted by the ratios shown in Table 8. This figure is estimated to be the most realistic depiction of the U.S. pork industry's footprint since it is a weighted combination of the two major analyses conducted. In Figure 18, Region 5 has a significantly lower footprint than the rest of the regions because the regionally sourced feed doesn't have a very large footprint for Region 5 (Figure 16A), and Region 5 was assumed to use exclusively locally produced corn and soy (Table 8). Due to the reduced water footprint, Region 5 would seem to be the best choice for hog farms, but gross generalizations could lead to unintended consequences. There is no substitute for evaluating each farm individually to make a well informed decision, based on multiple environmental and economic metrics. Regions 1, 2, 9 and 10 slaughter a relatively small number of pigs annually when compared to the rest of the United States and thus do not affect national averages to a great degree.

## 2.6. Conclusions

An LCA methodology was used to assess the scan-level water footprint of U.S. pork. Overall, the U.S. pork water footprint was estimated to be 8.2 gal/4oz (0.031 m<sup>3</sup>/4oz) serving of boneless pork with a total pork industry water use of 525,000,000,000 gal/yr (1,990,000,000 m<sup>3</sup>/yr) when analyzed using a weighted ration (that is based on a nationally weighted crop production) (Table 8). The feed ration footprint accounts for 83% to 93% of the entire pork supply chain footprint depending on the feed source. This is mostly water used to irrigate crops in the field. Feed crop water footprints can vary over 100 times in magnitude from one region to another. Intuitively, regions with more precipitation need less blue water for irrigation.

On-farm water usage accounts for approximately 13% of the pork industry's water footprint when commodity feed is assumed. The main components of the on-farm water consumption are drinking water, cooling water and washing water. Drinking water was the largest of the three contributors and is evaluated in more depth in the detailed LCA (Task C). Therefore, improved on-farm water efficiency techniques would have a significant impact on the total water footprint, especially reductions in the amount of water wasted from drinking systems. As stated in the literature review, replacing nipple drinkers with cup style drinkers placed at the appropriate height could reduce drinking water use by as much as 30% or 3% of the total pork supply chain water footprint.

The post-farm gate stages, processing, packaging, distribution, and consumer phases contribute a relatively small portion when compared to the cradle-to-gate water footprint. There is opportunity at the consumer phase for post-farm gate water savings through more efficient dish washing since dish washing makes up 90% of the consumer's water footprint and approximately 1% of the cradle-to-grave footprint. Ultimately, sourcing rain-fed feed crops rather than irrigated feed crops would lead to the largest reduction in the pork industry's water footprint.

## Chapter 3. Detailed LCA of Water Use

### 3.1. Introduction

The goal of this study was to analyze water usage in the U.S. pork industry using life cycle assessment (LCA) methodology. LCAs are quantitative analyses of complex systems for the evaluation of the impacts and risks associated with a production system. LCA can be an effective tool for comparing management strategies. An LCA of water use within the pork industry was performed, and the Pig Production Environmental Footprint Calculator (PPEFC) was enhanced with water consumption algorithms based on data from peer reviewed scientific literature and then the PPEFC was utilized to estimate the lifecycle inventory of water use. The work on this project was divided into the following tasks:

Task A. Literature Review for Water Footprints

Task B. Pork Supply Chain Scan-Level LCA of Water Use

Task C. Live Swine Production Detailed LCA of Water Use

Task D. Pig Production Environmental Footprint Calculator

This sub-report presents the results of the detailed LCA (Task C) and the Live Swine Production Water Footprint Calculator (Task D).

### 3.2. Detailed LCA of Water Use

#### 3.2.1. Goal

The primary goal of Task C was to perform a detailed assessment of water use in the pork supply chain in the U.S., from cradle to farm gate. The primary audience of this LCA is the pork producers who may use the results to identify opportunities to reduce water use, and in the support of other internal decisions for increasing the efficiency, profitability and security of the U.S. pork supply chain. This LCA is a cradle-to-gate detailed water footprint analysis of three production strategies at three scales across 10 regions.

#### 3.2.2. Functional Unit

The functional unit for the detailed LCA was defined as one pound of swine (live weight) at the farm gate.

### 3.2.3. System Boundaries and Scope

This life cycle assessment was a cradle (crop production for feed) to gate (live swine ready for transport to processing) analysis of the water footprint of U.S. pork production. Three swine production categories were included in this analysis:

1. Sow (Breeding/Gestation/Lactation)
2. Nursery
3. Growing/Finishing

Production practices included bedded hoop, total confinement/tunnel ventilated, and total confinement/drop curtains. Production categories and practices were analyzed for three production scales (100, 1200, and 2500 head barn capacity) across ten production regions (Figure 19, Table 9). It was assumed that all barns from a single scenario were located at a single facility and that there was an insignificant water footprint associated with the movement of pigs between barns. Effects embodied in infrastructure (e.g., water emissions associated with manufacture of new equipment necessary for farm equipment, which would be amortized over the expected life of the equipment) were not included in the analysis. Boar water footprints were not considered since boar-to-sow ratios are nearly 1:50 and each sow produces nearly 25 piglets per year, which would make for an annual boar to market hog ratio of 1:1250, and would fall below the 1% contribution threshold. Where data were incomplete, surrogate unit operations were identified from the EcoInvent database.

### 3.2.4. Scenario Development

The literature review and discussion with industry and National Pork Board (NPB) representatives helped refine the selected matrix of scenarios to be analyzed. The Pig Production Environmental Footprint Calculator was used to establish the on farm feed usage and water usage which were used as life cycle inventory data for the SimaPro LCA barn unit processes. Separate LCI models were created for the sow, nursery and grow-finish barns. The combined analyses of production strategies, production scales, production life stages, and production regions yielded a total of 240 scenarios that were analyzed; not all strategies applied to all scales or life stages (Table 10).



Figure 9. Swine Production Regions used in this analysis.

*Table 9. Scenario matrix of Live Swine Production Detailed LCA of Water Use. The sow life stage includes breeding, gestation and lactation.*

Production Strategy	Production Scale	Life Stage	Production Region
Drop Curtain	100	Sow	Region 1 (CT ME NH VT MA RI)
Tunnel Ventilated	1200	Nursery	Region 2 (NY NJ)
Hoop Barn	2500	Growing/Finishing	Region 3 (DE MD PA WV VA) Region 4 (AL FL GA KY MS NC SC TN) Region 5 (IL IN MI MN OH WI) Region 6 (AR LA NM OK TX) Region 7 (IA KS MO NE) Region 8 (CO MT ND SD UT WY) Region 9 (AZ CA HI NV) Region 10 (AK ID OR WA)

*Table 10. Scenario matrix of the production strategies that were analyzed for each scale. An "X" indicates that the combination was analyzed.*

Scale	Production Strategies		
	Drop Curtain	Tunnel Ventilated	Hoop Barn
100	-	-	X
1200	X	X	X
2500	X	X	-

### 3.2.5. SimaPro LCA Model

The SimaPro software platform was used for calculating the final water footprint for each of the 240 analysis scenarios. Data obtained from the literature review was used to create all of the input files and water algorithms for the PPEFC. As in the Scan Level LCA, aspects of the PPEFC output were used in a life cycle inventory for the life cycle analysis model developed in SimaPro V7.3 (Pre' Consultants, The Netherlands). The two models were used in series to produce cradle-to-gate water footprints for all 240 scenarios (Figure 20).

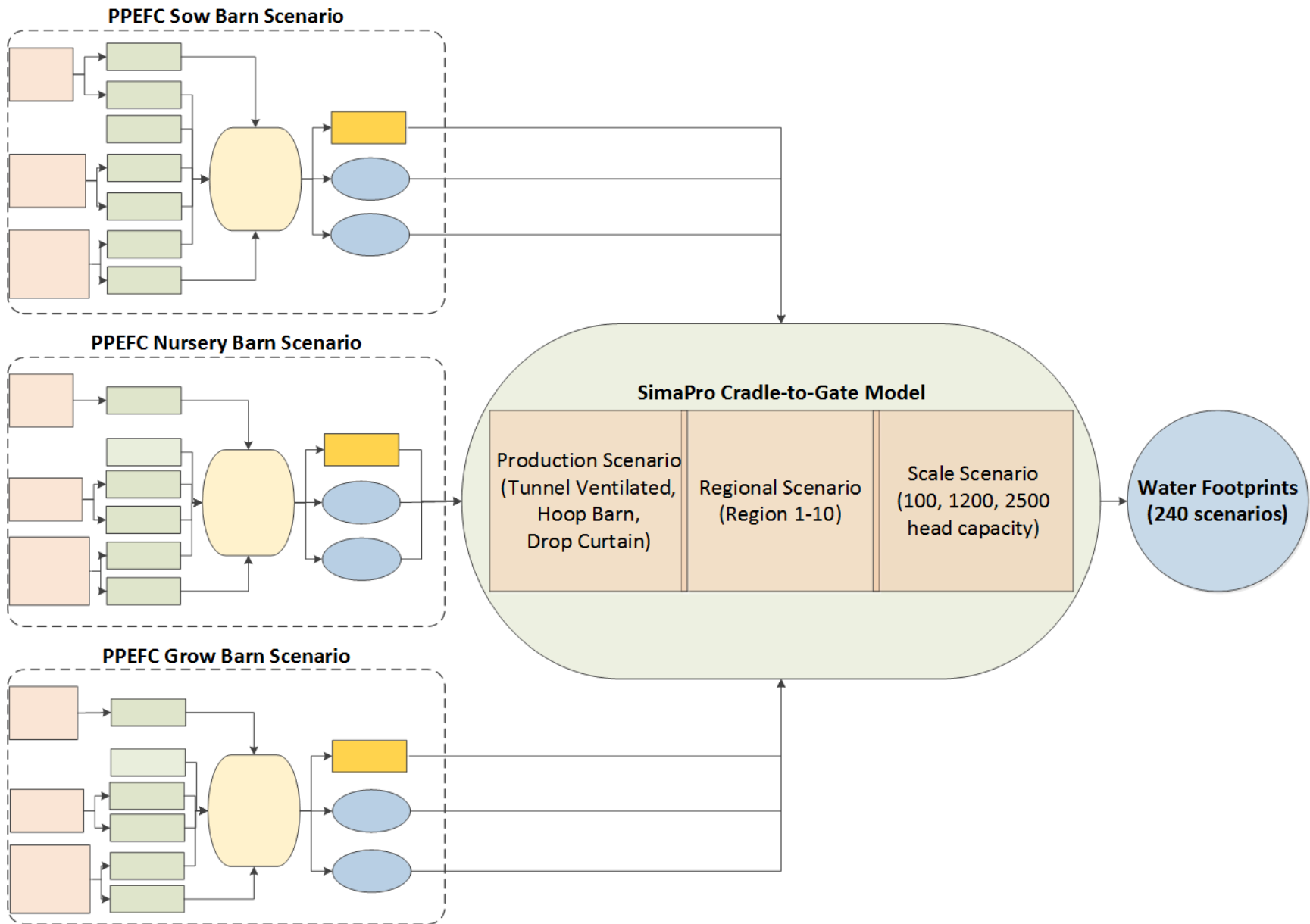


Figure 10. Network diagram showing the links between the Pig Production Footprint Model and the SimaPro model.



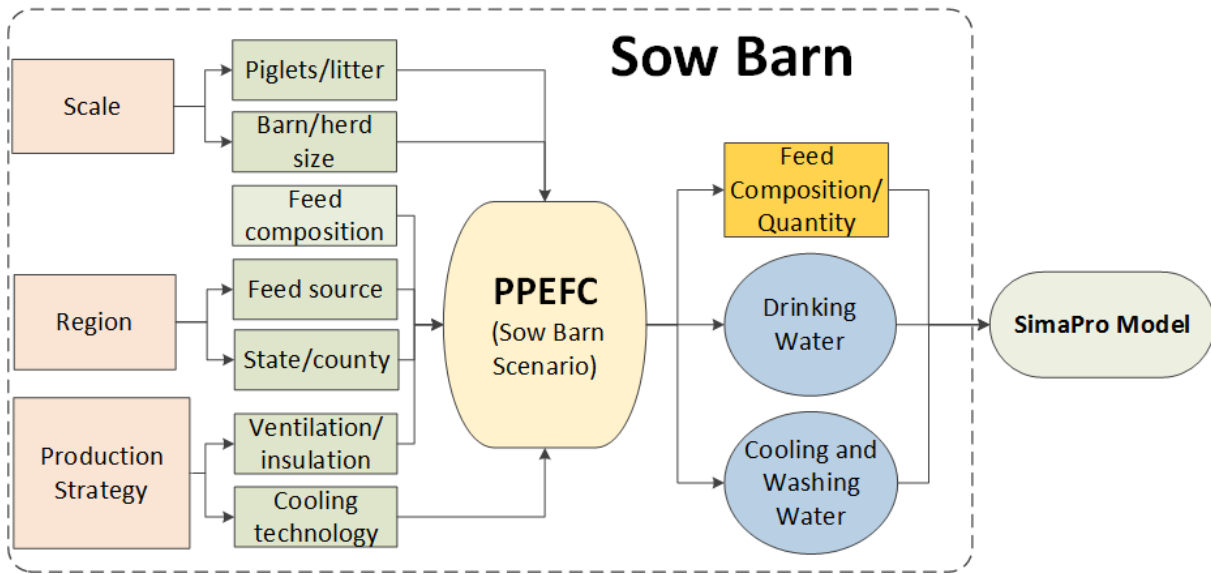


Figure 11. Sow barn Pig Production Environmental Footprint Calculator scenario in detail.

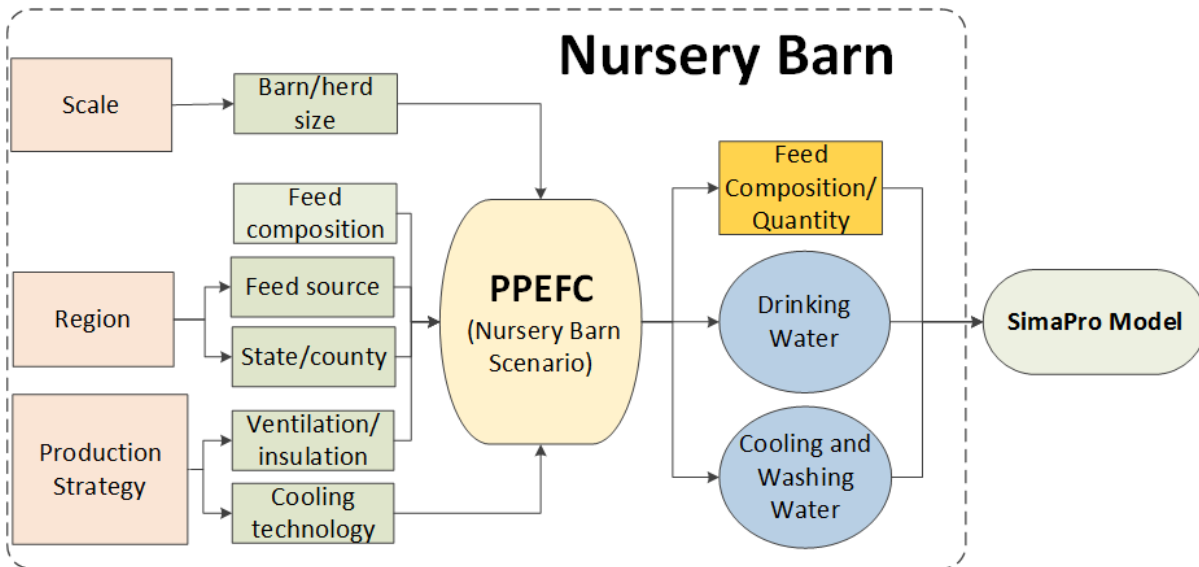


Figure 12. Nursery barn Pig Production Environmental Footprint Calculator scenario in detail.

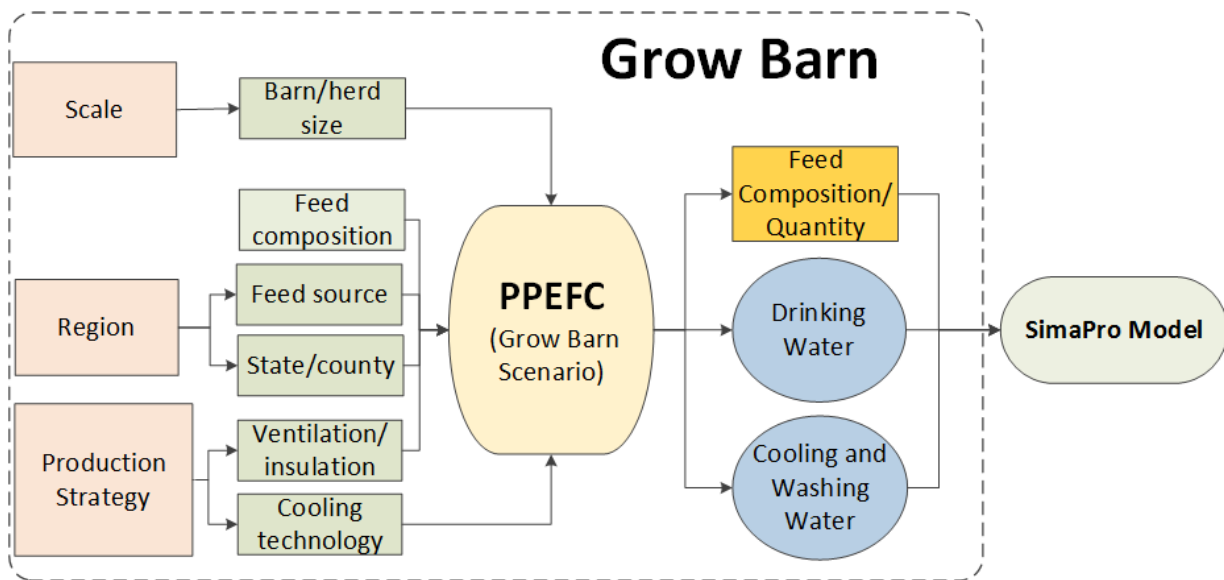


Figure 13. Grow barn Pig Production Environmental Footprint Calculator scenario in detail.

### 3.2.6. Life Cycle Inventory

The literature review conducted in Task A, combined with the Ecoinvent unit processes and the previously conducted Pork Carbon Footprint LCA (Thoma et al., 2011) served as the basis for much of the life cycle inventory data which were generated through the PPEFC. Additional discussions with industry representatives and other experts helped fill in the data gaps. The production system encompassed activities performed in support of pork production up to the farm gate.

#### 3.2.6.a Water Use for Crop Production

We employed the water use data for crop production described in the scan-level LCA (Task B). The regional data were weighted by production and irrigation water use to obtain national averages for corn and soybeans (meal component by mass allocation). The values for the national average blue water footprint for corn and soybean meal were 5.9 gal/lb (49.3 L/kg) and 7.2 gal/lb (59.7 L/kg), respectively. These commodity water footprints were used for all scenarios throughout the detailed analysis. This approach does not account for variation by region in animal rations. There is very limited, primarily anecdotal, information about this variation.

### 3.2.6.b Key Parameter Variations between Scenarios

The literature review conducted in Task A provided most of the inputs for on-farm water use. The detailed analysis used the same PPEFC model as the Scan Level Report, but varied the inputs to match, as nearly as possible, each production region, strategy and scale.

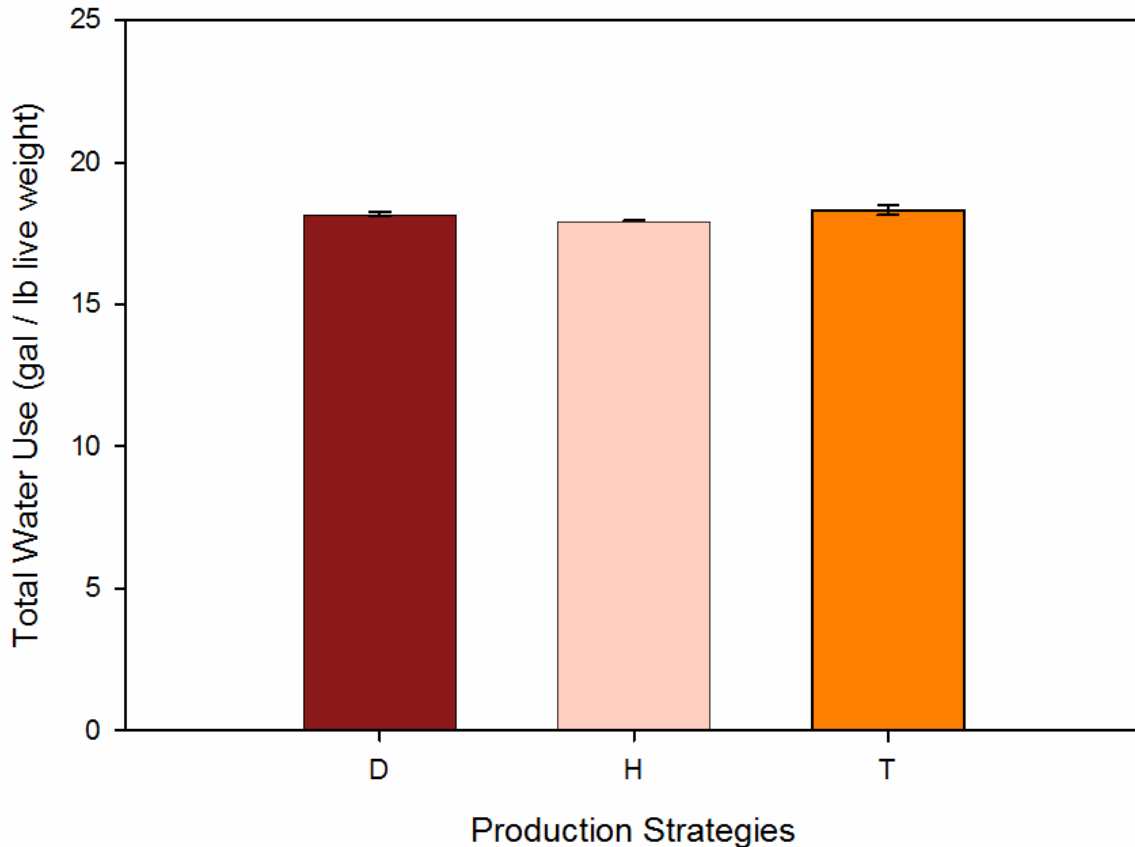
Adjusting the region in each scenario affected the daily temperatures which directly influence how often the heating and cooling systems are used in each barn. The heating systems have very little upstream embodied water, but the cooling systems are water based and can significantly affect the total footprint. In this analysis, it was assumed that tunnel ventilated barns had sprinklers with cool cells, drop curtain barns had sprinklers and hoop barns did not use water based cooling systems.

Drop curtain and tunnel ventilated barns were assumed to use the same volumes of washing water (per pig) between cycles. Since deep pit manure management systems are the most common, tunnel ventilated and drop curtain barns were modeled with deep pit systems. Blue water was used for washing the main floor and equipment, but it was assumed that any additional water for moving manure would be recycled water (not counted). The hoop barn scenarios used dry cleanup techniques without additional water for washing the barn floor.

The only quantifiable difference between the scale scenarios was the number of live piglets per litter. NASS surveys showed significant increases in piglet survival for larger facilities. For example, the 100 head facilities averaged 7.9 piglets/litter while the 2500 head facilities averaged 9.7 piglets/litter.

### 3.2.7. Results and Discussion

The pork blue water footprint varied with infrastructure and region. Total water use was greatest in the tunnel ventilated barn ( $18.32 \pm 0.18$  gal of water per pound live weight at farm gate; Figure 24). However, there was very little difference between the total water use of tunnel ventilated barns compared to the hoop barns ( $17.95 \pm 0.00$  gal/lb<sub>live weight</sub>) and drop curtain barns ( $18.18 \pm 0.09$  gal/lb<sub>live weight</sub>). Hoop barns did not have a standard deviation because the hoop barn footprint does not vary by region alone (Figure 24). Although, animal drinking water consumption is expected to be higher in hoop barns located in arid regions with higher summer temperatures than in temperate regions with lower summer temperatures, Version 2.0 of the PPEFC did not have comprehensive enough algorithms to model climatic effects on pig performance or water consumption. As a result, barns with water based cooling systems (drop curtain and tunnel ventilated) use more water in warmer climates. The hoop barn uses less water for cooling systems, but the climate inside the barn may adversely affect pig performance. The variation from the region is due to heating and cooling within the barns based on model structure, but hoop barns were modeled with no heating or cooling systems that require additional resources.



*Figure 24. Total cradle-to-gate blue water use by barn type: drop curtain (D), hoop barn (H), and tunnel ventilated (T). The three totals are 1200 head scenarios averaged across all 10 regions.*

Regionally, total water use per pound of live weight showed consistent trends (Figure 25). The tunnel ventilated barn water footprint was consistently higher, followed by the drop curtain and then the hoop barn in each of the regions. In region one, all three of the footprints were nearly the same since the colder climate does not have as many high temperature days, so cooling water is not necessary. The driving differences between regional footprints were climate, since all regions were using commodity sourced feed in this analysis. Variation in production strategies between regions was not accounted for other than in the heating and cooling technologies required to compensate for outside temperatures and relative humidity. Since the hoop barn doesn't use cooling systems, the water footprint remained steady from region to region. Tunnel ventilated barns were modeled with the most water based cooling systems which provided them better climate control, but consequently used more water in warmer climates. That explains why the southern Regions of 4, 6 and 9 had the most water consumption in the barns using water based cooling systems. Due to inconsistent trends from the available literature, this analysis did not account for the complex changes in pig health, behavior or performance due to climatic conditions.

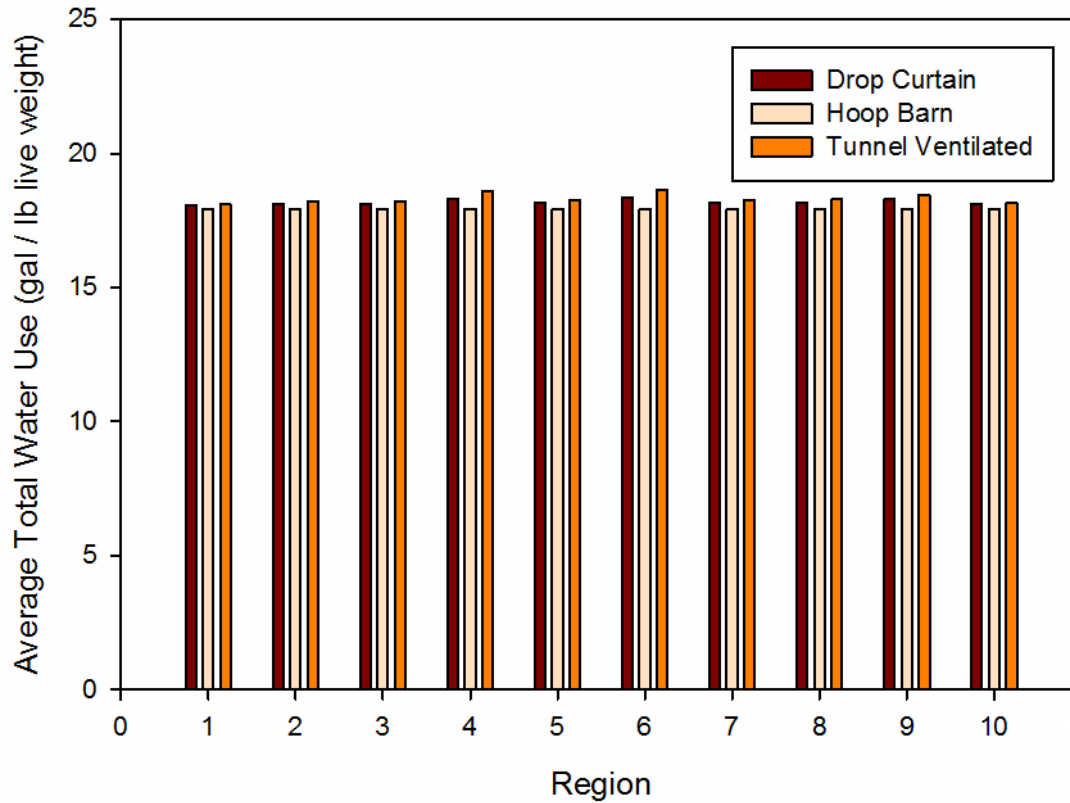


Figure 25. Total water use across for each barn type in each region. These totals have been averaged from the 1200 head scenarios.

Across the swine production life stages the greatest water use comes from the grow barn while the sow and nursery barn had much smaller water footprints in all three barn infrastructures (Figure 26). The higher grow barn footprint can be attributed to the longer period of time and larger increase in pig weight in the grow barn than the nursery barn. Sows consume three to four times as much water per pig space than a grow/finish pig, but that footprint gets distributed over all of the piglets (8 – 10 piglets/litter) they produce.

The box whisker plots in Figure 26 have boxes representing the 25th and 75th percentiles and dots at the 5th and 95th percentile points. Some of the model outputs (hoop barn) have so little variation in the data that the 25th to 75th percentile boxes look more like lines.

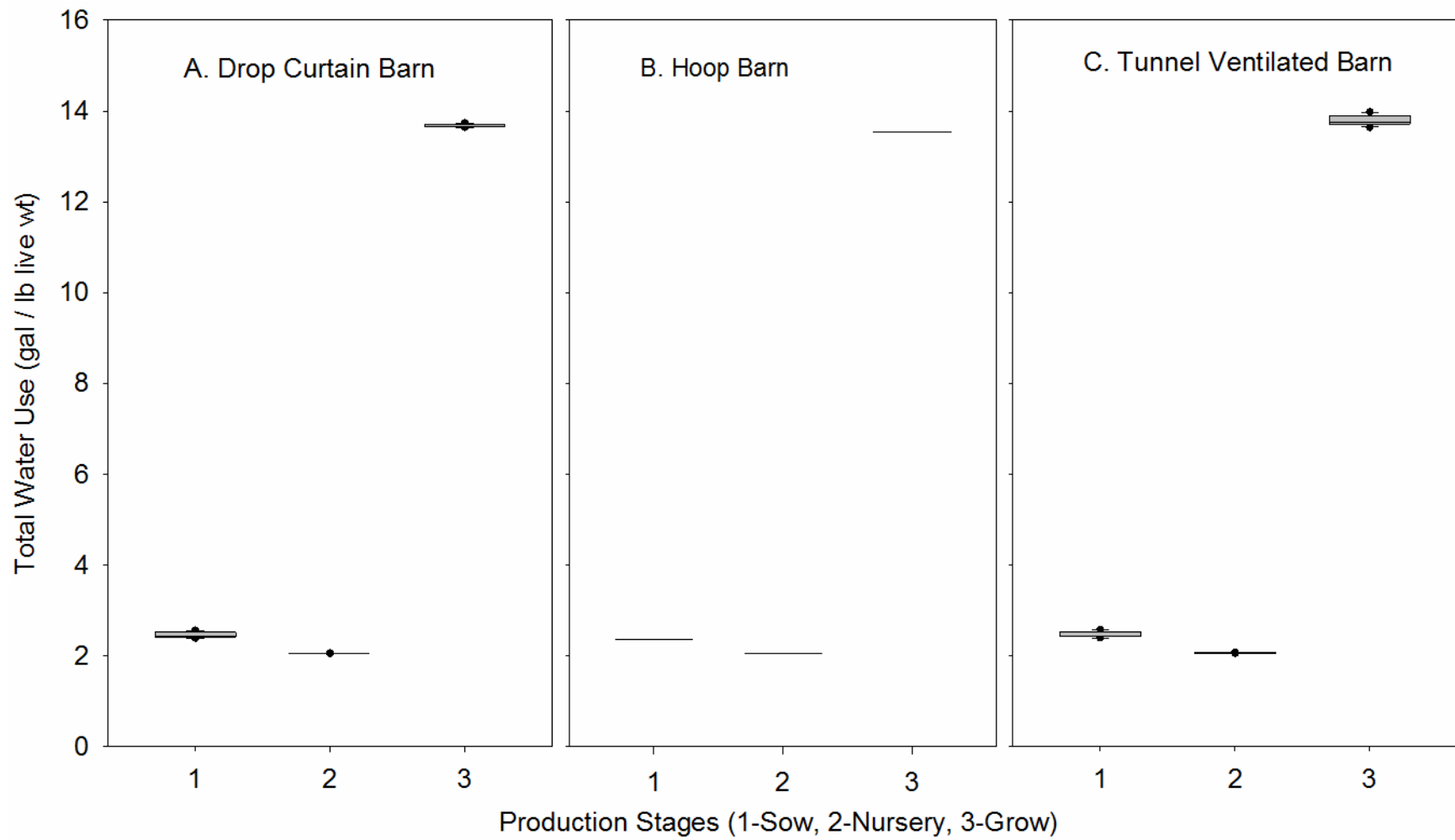


Figure 26. Total water use across swine production stages for each barn infrastructure type.

In this analysis, drinking water and food consumption algorithms were assumed to remain constant between all scenarios, because data were not available to support precise variances. Since the ration (90%) and drinking water (9%) footprints make up nearly 99% of the cradle-to-gate footprint, those assumptions do not allow for much variation in the model outputs (Figure 27). Cooling water and washing water contribute about 11% of the facility footprint with the remainder from drinking water. The calculated ration footprint was larger than the 67% ration footprint estimated using data and methods from Mekonnen and Hoekstra (2011) (see Literature Review). In their study, Mekonnen & Hoekstra (2011) used low resolution datasets to perform global comparisons of agricultural products. This LCA used data from literature specific to North American pork production to create a more detailed and relevant assessment of U.S. pork production. It is clear that drinking water consumption and delivery play a relevant role in the water use efficiency of swine production. Resources put into higher efficiency drinking systems would be much more valuable in terms of water reduction than cooling and washing systems. The “other” water in the pie chart below is made up of many small fractions of water embodied in upstream supply chain processes such as energy production. The “other” category is not an easy target for water reductions.

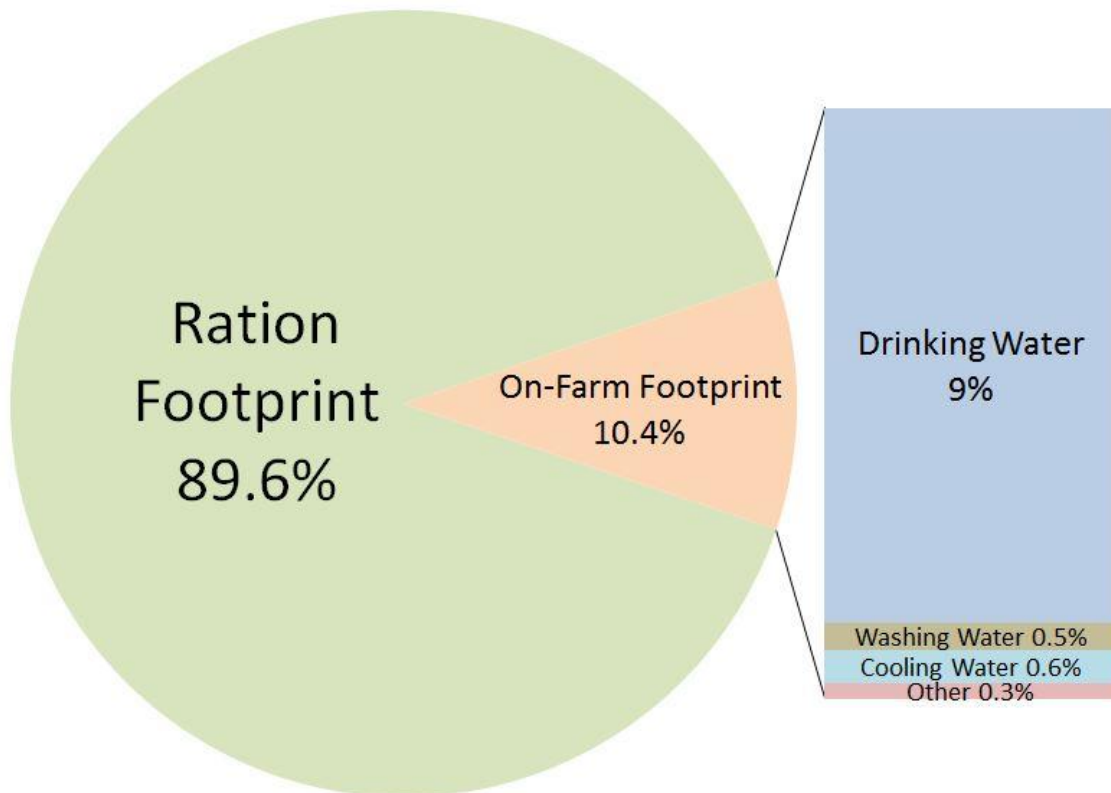


Figure 27. Cradle-to-gate blue water footprint contribution to U.S. pork production, averaged from all 240 cradle-to-gate scenarios.

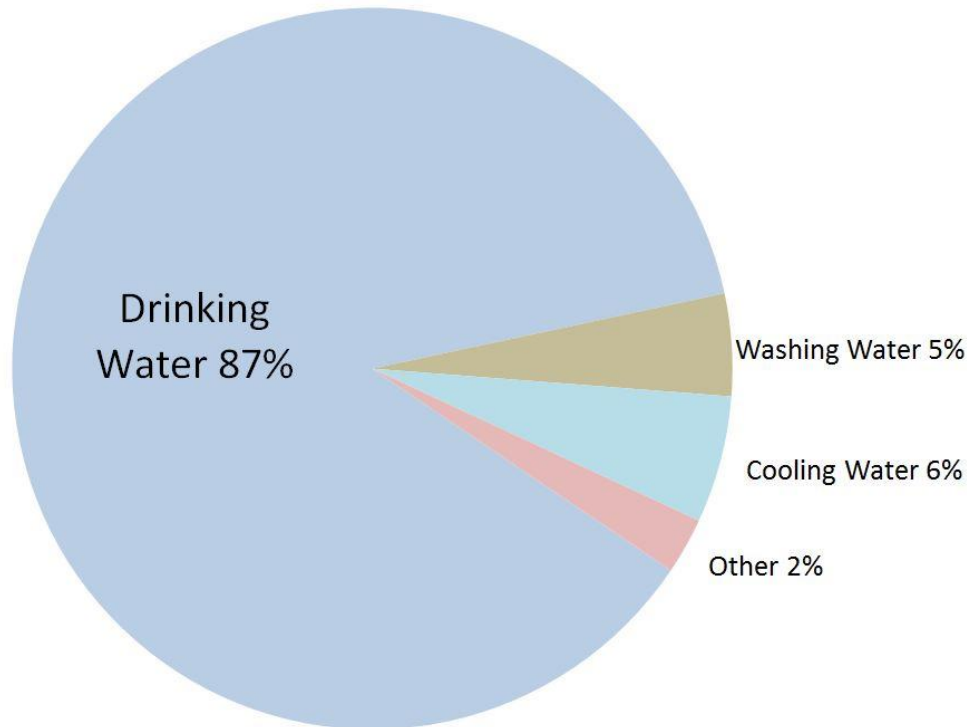


Figure 28. Breakdown of contributions to the on-farm water footprint in U.S. pork production. "Other" is mostly made up of water embodied in barn infrastructure and energy.

### 3.2.8. Sensitivity and Uncertainty Analysis

#### 3.2.8.a Sensitivity Analysis

A sensitivity test of the model inputs was conducted to evaluate the robustness of the study's conclusions. The model input parameters identified in Table 10 were individually analyzed to gauge the sensitivity of the model output (water footprint). Each of the parameters was varied under *ceteris paribus* conditions (all other things remaining equal) by an increase and decrease of 10% to quantify the effect on the cradle-to-gate water footprint. The first iteration of the sensitivity analysis was an upper-level analysis that showed swine rations to have the most significant effect on the model output. We followed this with individual sensitivity analysis on all of the significant ration components to determine which ones had the greatest effect on the model output.



*Table 11. Pig Production input parameters tested for sensitivity.*

Upper Level Parameters		Ration Parameters	
Piglet heaters	Drinking water	Limestone	Ronozyme
Fans	Ration	Monocalcium Phosphate	Tallow
Lights	Washing water	Sodium Chloride	Plasma
Barn infrastructure	Transportation	Soybean Meal	L-Lysine HCL
Heaters	Nitrous Oxide	Trace Mineral Mix	DDGs
Gilt production	Methane produced	Vitamin Premix	Corn Grain
Manure spreading	Cooling Water	Dry Whey	

### 3.2.8.b Uncertainty Analysis

We used stochastic modeling methods to quantify and characterize uncertainty in the LCA results. It is important to understand that all of the water footprints calculated in this study were based on estimated values that have an associated range of uncertainty. Any conclusions from the results must therefore be made in the context of the uncertainties in the underlying data. This analysis is crucial for establishing defensible metrics for evaluating the progress toward a more sustainable supply chain.

Uncertainty is classified in two major types: knowledge uncertainty and process uncertainty. Knowledge uncertainty reflects limits of what is known about a given parameter, while process uncertainty reflects the inherent variability within a process or parameter. Knowledge uncertainty can be reduced by collecting more data to decrease the possible range of the parameter estimate. Process uncertainty is random variability which is a property of the system and may be better defined with more data, but generally cannot be reduced.

Each output of the PPEFC was represented as either a lognormal or triangular distribution (Table 12) to serve as an input to the SimaPro model. A 1000 run Monte-Carlo simulation was performed to characterize the probability distribution for the water footprint. Any foreground processes without an already established uncertainty distribution were assigned an inherent uncertainty of  $\pm 20\%$  when used in the Monte-Carlo simulations. The result was a distribution for the water footprint rather than an average value. These distributions quantify the associated uncertainty in the results about the mean value. Uncertainty analysis was performed across regions, scales and production strategies. The combination of models used in this LCA is more useful for identifying differences between regions, production strategies, life phases and scales than it was for producing absolute footprints.

Table 12. Select parameter assignments for uncertainty analysis.

Type	Units	Distribution	Average	SD <sup>2</sup>	Min	Max
Gestating Sow Drinking	gal/pig/day	Lognormal	4.6 <sup>1, 2, 4, 7</sup>	1.27	3.5	6.4
Lactating Sow Drinking	gal/pig/day	Lognormal	6.8 <sup>1, 2, 4, 7</sup>	1.32	4.8	9.9
Nursery Drinking	gal/pig/day	Lognormal	0.8 <sup>1, 7, 9</sup>	1.15	0.7	0.9
Grow Drinking	gal/pig/day	Lognormal	1.5 <sup>1, 5, 6, 7, 8</sup>	1.56	1.4	2.1
Finisher Drinking	gal/pig/day	Lognormal	2.2 <sup>1, 3, 4, 6, 8, 12</sup>	1.42	1.4	4
Sow Washing	gal/pigspace/wash	Triangle	35.9 <sup>10, 13</sup>		22.5	84
Nursery Washing	gal/pigspace/wash	Triangle	3.2 <sup>10, 13</sup>		1.6	6.9
Grow Washing	gal/pigspace/wash	Triangle	7.4 <sup>10, 13</sup>		4.3	10.5
Live Transport Washing	gal/pig/wash	Triangle	3.9 <sup>10</sup>		3.75	4.05
Sprinkler Cooling	gal/pig/hr	Lognormal	0.1 <sup>11</sup>	1.51		
Drip System Cooling	gal/pig/hr	Lognormal	0.8 <sup>11</sup>	1.51		
All Rations		Lognormal		1.2		

<sup>1</sup>Almond, 1995; <sup>2</sup>Almond, 2002; <sup>3</sup>Amornthewaphat et al., 2000; <sup>4</sup>Brumm, 1999; <sup>5</sup>Brumm, 2006; <sup>6</sup>Christiansen, 2002; <sup>7</sup>Froese, 2001; <sup>8</sup>Li, 2005; <sup>9</sup>Margowen, 2007; <sup>10</sup>Muhlbauer, 2010; <sup>11</sup>MWPS, 1991; <sup>12</sup>Rantanen, 1994

### 3.2.8.c Sensitivity Analysis Results

Sensitivity analysis is a useful approach to help answer the question: “What information is most critical to collect to ensure high quality?” In the following charts, it is important to keep this question in mind and not to conclude that changing an operating characteristic of the facility to match the change in the parameter will result in an equivalent increase or reduction of the water footprint, but an indication of the level of accuracy required for that input into the LCA model to reduce the error in the model output. The swine production inputs were evaluated to determine the degree of influence that a 10% change in the parameter value would have on the final results. We used a threshold value of 0.5% or more change in impact to identify sensitive parameters. Parameters which were not reported were not identified as sensitive since a 10% change in that input resulted in less than 0.5% change in water footprint. Not surprisingly, the feed ration and its associated production processes (corn grain, soybean meal, and dry whey) had the greatest impacts (Figure 29), which is similar to findings reported in the literature review (Task A). In Figure 29, the percent change caused by the ration parameter is essentially the sum of corn grain, soybean meal, dry whey and the remaining feed components. Intuitively, corn grain and soybean meal noticeably affect the final footprint when their model input value is adjusted up and down

by 10%. Dry whey's effect on the cradle-to-gate footprint is surprisingly large when considering that within this model, whey was only fed to nursery pigs and it was less than 5% of the total weight of the nursery ration.

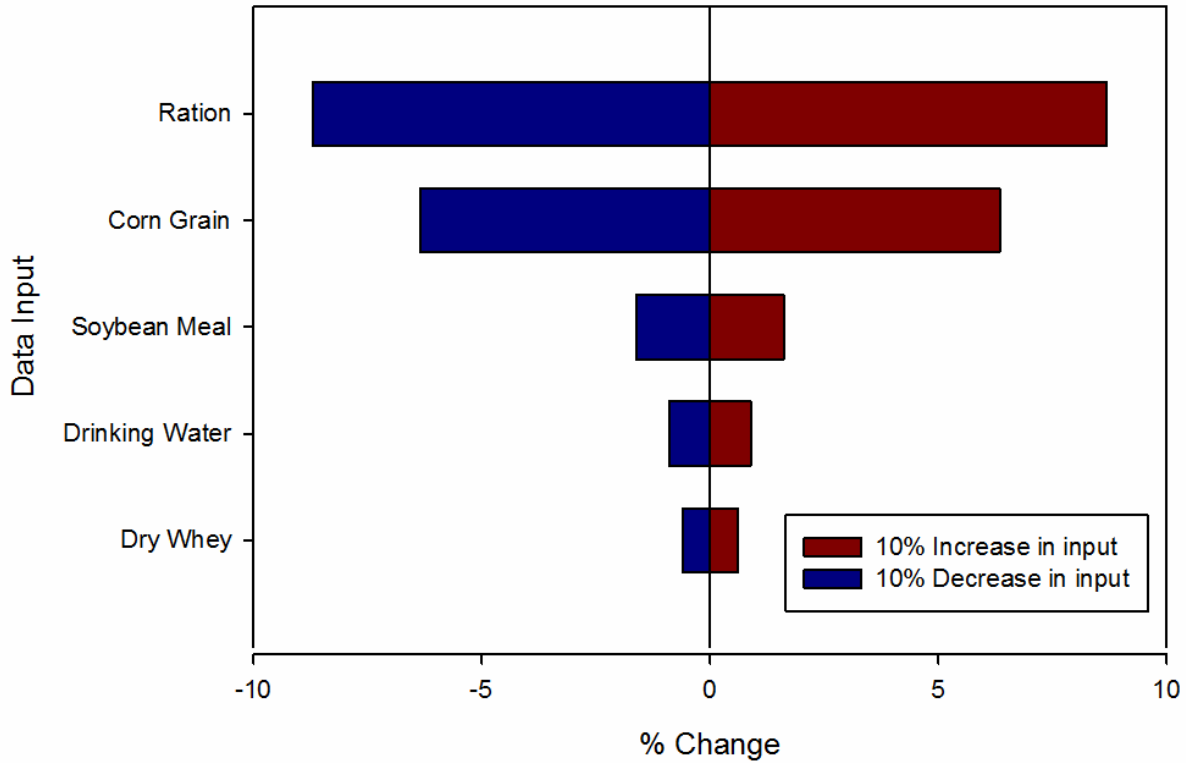


Figure 29. Tornado diagram showing the sensitivity of parameters to uncertainty in the water footprint for a 10% increase and decrease in parameter value. The "% Change" refers to the variation in the cradle-to-gate water footprint due to the parameter variation.

### 3.2.8.d Uncertainty Analysis Results

The results of the Monte Carlo simulations for the uncertainty analysis are presented as box and whisker plots (Figure 30, Figure 31, and Figure 32). The boxes define the 25th and 75th quartile distributions, the solid line within the box represents the median, and the blue dash line represents the mean of the Monte Carlo simulations. The lower and upper error bars (whiskers) define the 10th and 90th percentiles respectively. Dots below and above the error bars represent the outlying points. It is important to remember that all of the water footprints calculated in this study were based on estimated values that have an associated range of uncertainty. The potential water footprints could lie anywhere among the 1000 Monte Carlo runs, but will have an 80% chance of falling within the whiskers (Figure 30, Figure 31, and Figure 32).

As an example, in Region 7 (Figure 30), the 10th percentile was approximately equal to 16.2 gal/lb live weight (0.14 m<sup>3</sup>/kg) 90th percentile was approximately equal to 22.6 gal/lb live weight (0.19 m<sup>3</sup>/kg). The interpretation of this result is that we can state with 80% confidence that swine produced in Region 7 will have a water footprint between 16.2 gal/lb live weight and 22.5 gal/lb live weight.

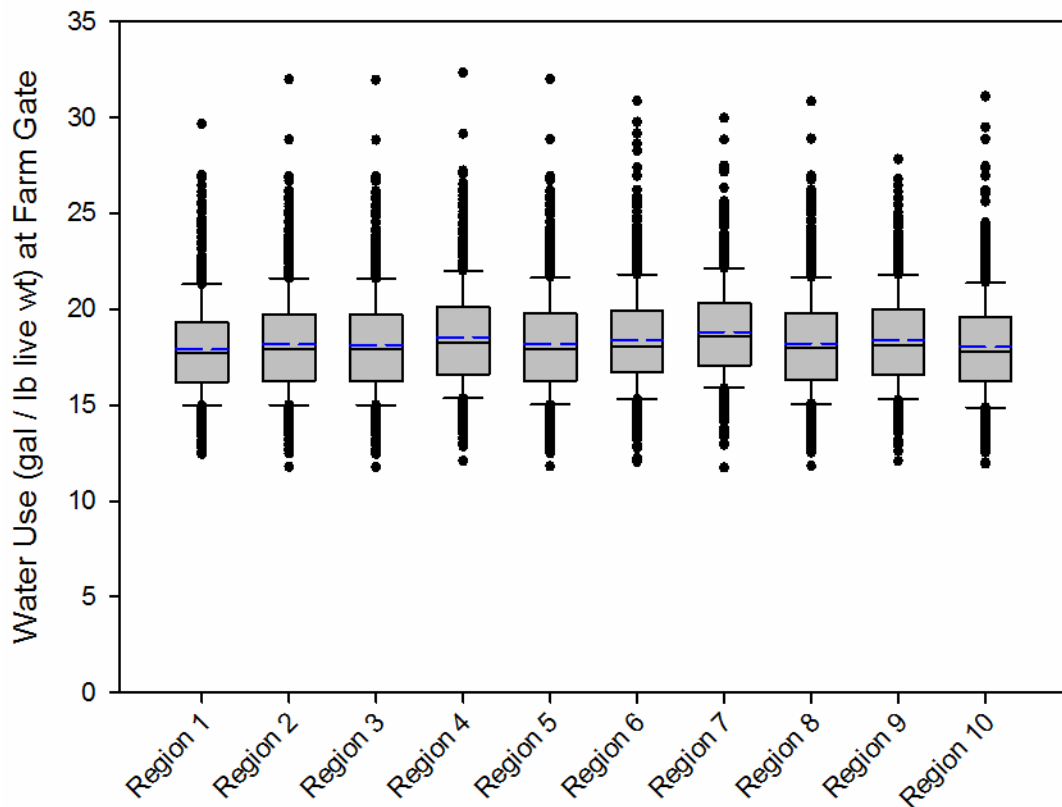


Figure 30. Estimated potential change in water footprint for U.S. Swine production across 10 regions. All footprints are 1200 head tunnel ventilated facilities.

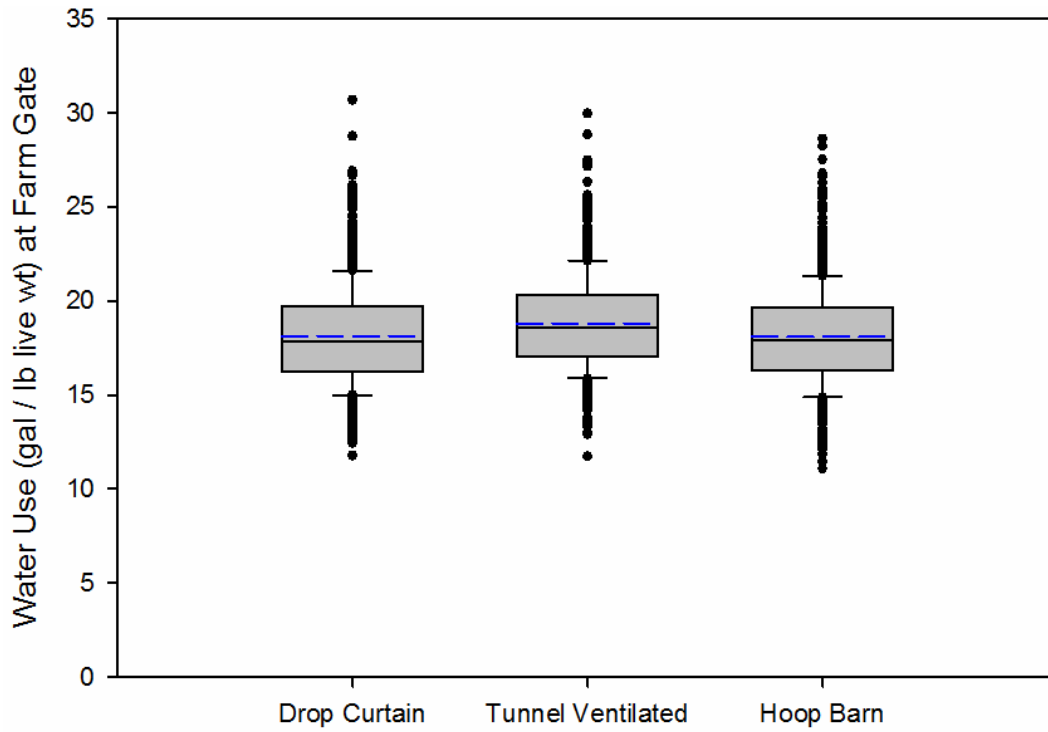


Figure 31. Estimated potential change in water footprint for three U.S. swine production strategies. All footprints are 1200 head facilities located in Region 7.

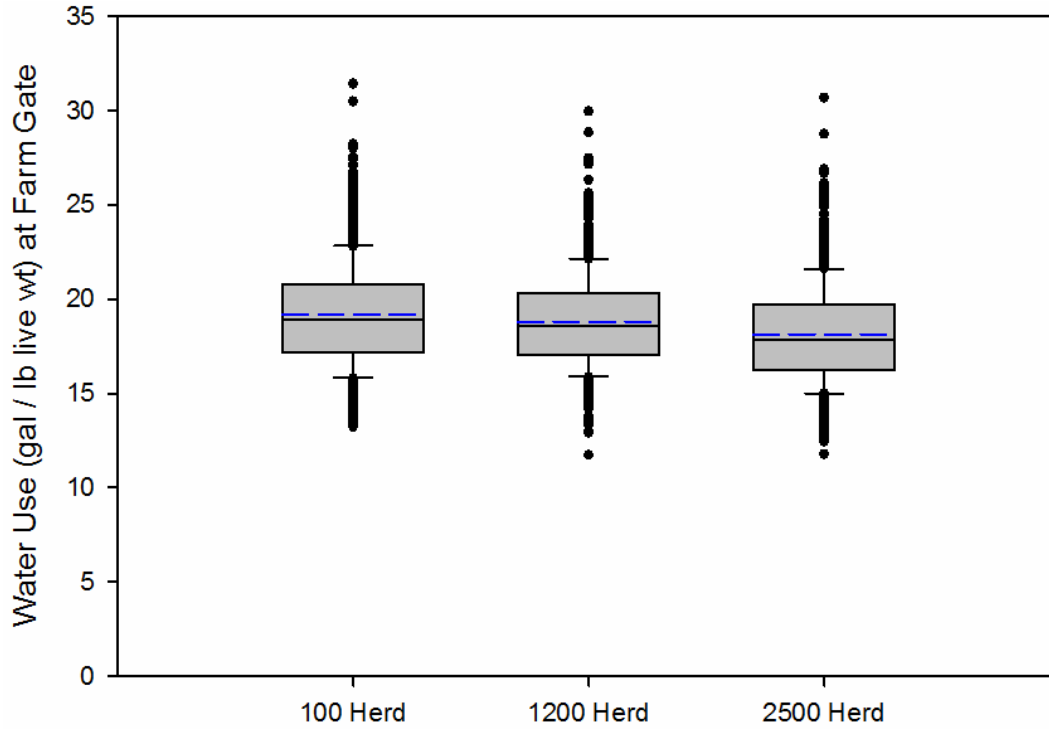


Figure 32. Estimated potential change in water footprint for three U.S. swine production scales. All footprints are tunnel ventilated barns in Region 7.

A similar conclusion can be drawn from the swine production strategy scenarios (Figure 31). The swine produced using a tunnel ventilated infrastructure were estimated to have a slightly higher water footprint than the drop curtain and the hoop barn. All of the variation between barn types is driven by the different cooling technologies' water use requirements. Tunnel ventilated barns were assumed to use sprinkler systems supplemented by cool cells, while drop curtain barns only used sprinklers and hoop barns did not use water cooling systems. Of course, different configurations are used in practice, but no demographic information is available to determine a weighted average of technology adoption. Therefore, these results primarily highlight the differences in cooling technology rather than barn type directly.

An apparent contradiction results between Figure 31 and Figure 32, where tunnel barns have larger water consumption but larger barns have lower consumption. This is explained by noting the herd size effect could be viewed as another dimension of the barn type analysis, and that the observed economy of scale would apply to each of the barn types in Figure 31.

When considering the scale of production in Figure 32 for tunnel barns only, the 1200 and 100 head facilities had higher water footprints than the 2500 head production scale. One factor causing the 2500 head scale to have a lower water footprint per mass of pig is the higher ratio of piglets per litter in larger operations (NASS, 2013). Since the functional unit is live weight ready for transport to slaughter, the sow's water consumption is assigned to her piglets; higher piglet survival rates in the larger operations reduce the relative contribution of the sow's consumption per pig in those systems. Due to economies of scale, it is intuitive that larger farms may be more efficient, but our model did not show significant effects. The PPEFC does account for the thermodynamic efficiencies of a larger building and we did see a modest decrease in heating and cooling requirements per pig for the larger scale barns.

### 3.3. Pig Production Environmental Footprint Calculator

Task D was accomplished by integrating the literature review of swine production water use into the Pig Production Environmental Footprint Calculator (Figure 33). This included equations for drinking water, cooling water and wash water use:

$$\text{Wash water per pig per yr} = f(\text{number of cycles per yr, barn infrastructure})$$

$$\text{Drinking water} = f(\text{pig weight})$$

$$\text{Cooling water} = f(\text{climate, barn thermodynamic properties, evaporative pad, sprinkler or drip})$$

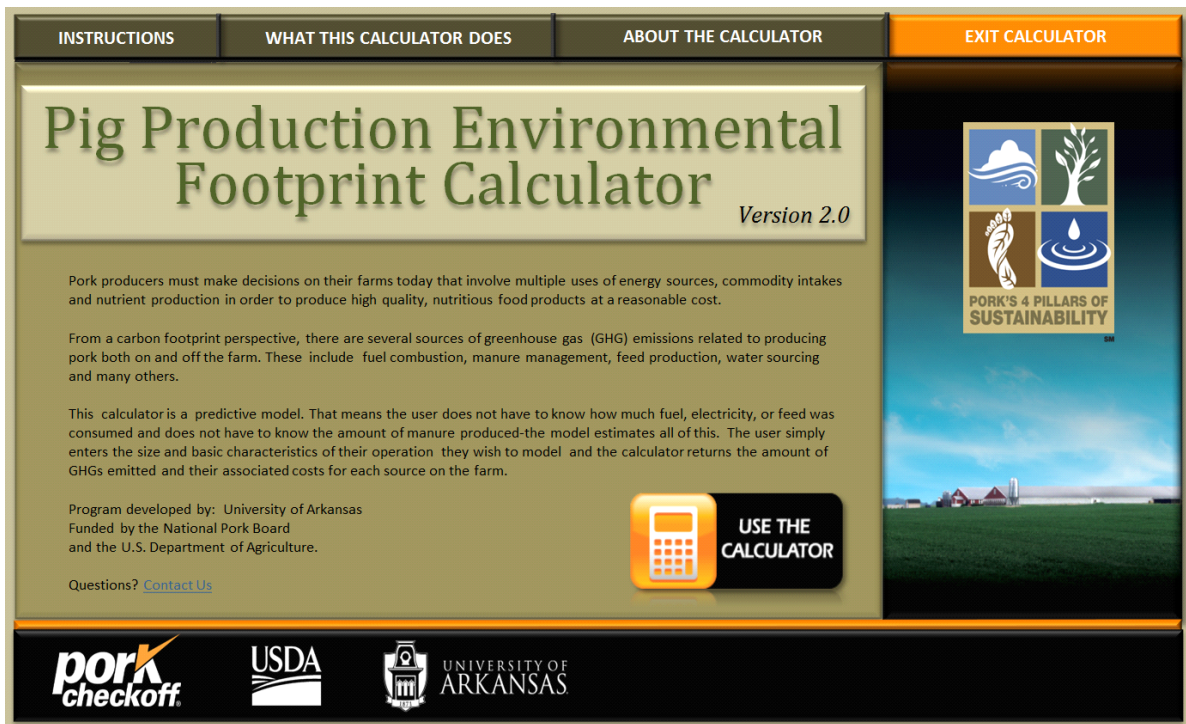


Figure 33. Interface of the Pig Production Environmental Footprint Calculator used in calculating water use for swine production.

The PPEFC is now able to calculate the volume of water consumed by the pigs per year, the water consumed in cooling cells, the water required for barn washing and the volume of water required for evaporative pad, drip or sprinkler systems in the barn infrastructure. The drinking water model used during this study did not link drinking water to feed intake. Future versions of the PPEFC animal performance module will include algorithms that account for the effects of feed intake and environmental conditions on drinking water consumption. The simplification of the complex processes within the live swine facility is intrinsic to modeling and produces outputs that should be viewed with these shortcomings in mind.

### 3.4. Conclusions

The detailed cradle-to-gate analysis of U.S. pork production showed water use ranged 18.38-18.94 gal/lb<sub>live weight</sub> (0.153-0.158 m<sup>3</sup>/kg<sub>live weight</sub>) across production strategies and regions. The tunnel ventilated barn water footprint was consistently higher (18.65±0.18 gal/lb<sub>live weight</sub> at farm gate), followed by the drop curtain (18.50±0.09 gal/lb<sub>live weight</sub>) and then the hoop barn (18.38±0.00 gal/lb<sub>live weight</sub>) in each of the regions. It should be noted that the differences between barn types was driven by the assumed systems used for cooling. For example, tunnel ventilated barns were assumed to use the most water based cooling systems whereas hoop barns were assumed to have no water based cooling systems. Although the hoop barn has been shown to use less water in hot regions, this may be misleading because animal performance is likely to suffer during periods of extremely hot weather without dedicated cooling systems. As the model is improved to account for these *in vivo* tradeoffs a more complete understanding of the impacts and tradeoffs associated with using hoop barns as opposed to other housing systems will become clearer.

Regions 4, 6 and 9 had the highest water use since they were the southern regions with higher average temperatures which required more use of water based cooling systems. The regional comparison did not yield substantial variation, since all rations were assigned commodity feed water footprints. When considering the total water use by production phase, the Grow/Finish phase accounted for approximately 75% of the footprint (including feed production) when compared to the sow and nursery life phases. The water embodied in the feed drove the grow/finish phase to have a larger footprint since that life phase required the most feed. The larger scale facilities had marginal decreases in water footprint due to increases in piglets/litter and improved climate control efficiencies.

Overall the results show that rations account for approximately 90% of the cradle-to-gate water footprint. Drinking systems are the second most significant contributor to the water footprint, and represents 9% of the total cradle-to-gate water footprint and 87% of the on-farm water footprint. Water used in drinking systems is not only a significant contributor to the footprint, but there is an opportunity for water reduction by implementing more efficient drinking systems, as stated in the literature review. Replacing nipple drinkers with cup style drinkers placed at the appropriate height could reduce drinker water use by 20-31% and thus reduce the total pork supply chain water footprint by 1.8-2.7%.

Cooling water and washing water were not insignificant contributors to the water footprint, but they are relatively small and are not likely to be easy opportunities for improved efficiency. Ultimately, sourcing rain-fed feed crops rather than irrigated feed crops would lead to the largest reduction in the pork industry's water footprint.



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