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Energy and nutrient cycling in pig production systems

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CHAPTER 1. GENERAL INTRODUCTION

Life depends on three inter-woven basics: energy, nutrients, and a supporting environment. This dissertation is an examination of those three basics under the context of complementary crop and pig production in Iowa. The ultimate goal is to provide useful information to the general public, students, policy makers, and fellow academics about the potential impacts of different pig production systems. An overarching assumption of this dissertation is that pigs and crops will be raised in Iowa and that human society will not spontaneously alter its *modus operandi*. It is my hope that with information based decision making we can better address the mounting challenges we face and foster the advancement of a more sustainable agriculture.

United States pig production is concentrated in Iowa, and is a major influence on the economic and ecological condition of that community. A pig production system includes buildings, equipment, feed ingredients, feed processing, and nutrient management at the individual farm level. Energy is used in all aspects of pig production, from the manufacture of materials used in building construction to the cultivation and processing of feedstuffs. Historically the availability of fossil fuels has minimized pressure to consider all uses of non-solar energy in pig production. Rising energy prices, uncertain access to petroleum supplies, and recognition of the environmental impacts of using fossil fuels are increasing awareness and incentives to reduce the use of limited non-solar energy resources. Comprehensive, accurate information is critical to informed decision making. Analysis of non-solar energy use by modern pig farms in the state of Iowa, the Midwest region, and the United States is lacking.

Greenhouse gas emission by human activity impacts the supporting environment that all Earth-based life relies on. The emission of greenhouse gases by agriculture is impacted by both crop and livestock sectors. Consumption of energy results in emission of greenhouse gases. If non-solar energy use in the construction and operation of a pig farm can be minimized, greenhouse gas emissions may decline. Both carbon sequestration and soil erosion potential is heavily influenced by cropping systems and indirectly affected by diets fed to pigs. If a perennial crop such as alfalfa could be incorporated into the feeding regime of pigs, there may be potential for decreasing losses of soil and soil bound nutrients due to erosion and generation of soil organic matter through carbon sequestration.

Nutrient cycling within an agricultural system can greatly impact energy use by that system. Internal cycling of nutrients such as occurs when pig manure is returned to fields producing the crops that ultimately feed the growing pigs may lower the need for synthetic sources of fertility. Synthetic forms of fertility typically require significant amounts of energy to generate and transport. Thus utilizing locally produced, animal-based sources of fertility can lower the non-solar energy use of crop production. Nutrients can also move from a pig production system to air and water and thus impact the supporting environment.

Energy use, nutrient cycling, and ecological impacts on the global environment of agricultural systems are not isolated events or entities. Rather they are interconnected influences which must be considered simultaneously when evaluating the desirability of a given production system, or when designing an agroecosystem suitable for a particular landscape. Models are simplified representations of complex reality and as such allow modelers to predict likely trends within a system as well as the magnitude of changes resulting from management decisions. The utility of a model obviously relies to a great extent on the accuracy of modeling assumptions used as well as correctly representing the relationships and interactions that occur within a system. Although imperfect, models can be powerful analytical tools. Thus to predict the comparative non-solar energy use and ecological impacts of different pig production systems a series of complimentary and interconnected models were developed and used.

This dissertation quantifies non-solar energy use in the construction and operation of pig production systems in Iowa. A pig production system includes buildings, equipment, feed ingredients, feed processing, and nutrient management at the individual farm level. Non-solar energy use, nutrient cycling, and environmental impact by different phases of pig production, under different diet and facility scenarios are modeled and compared using process analysis methodology. All energy inputs (direct and indirect) into a pig production system are considered based upon physical material flows. Direct energy is used within the system for agricultural production. Diesel fuel, electricity, and feed use are examples of direct energy. Energy used to produce farm inputs such as mineral fertilizers, seeds, gates, building materials and equipment are examples of indirect or embedded energy. For this project, indirect energy use one-step backwards from the farm is considered e.g. the energy used to produce gates and feeders will be included but not the energy used to manufacture the equipment to produce the gates and feeders. Energy and material flows within and out of a pig production system are compared to energy and material flows into the system in order to calculate energy use efficiency.

DISSERTATION ORGANIZATION

This thesis is divided into a literature review, six papers, a general summary, and three appendices. The six manuscripts that comprise the bulk of this dissertation have been published, accepted for publication, or are awaiting submission to an appropriate scientific journal and are individually formatted according to the guidelines of each journal.

CHAPTER 2: LITERATURE REVIEW

ENERGY

There are two broad categories of energy—embodied and operating. Embodied energy is the energy required to produce, manufacture, provide, or supply a product, material, or service (Hammond and Jones, 2008b). In pig buildings, energy used to manufacture facility components such as concrete, steel, and plastics are examples of embodied energy. Operating energy is the energy directly used by a system to function on a daily basis. In pig buildings, electricity to operate ventilation systems, liquefied petroleum gas to heat buildings, and diets fed to pigs are examples of operating energy. To borrow terminology from economics, operating energy can be considered analogous to variable costs—costs (energy use) that are incurred only if pig production occurs. Alternatively, embodied energy can be viewed as fixed costs—costs (energy use) that are incurred to create and maintain the means of production even if no pigs are actually raised.

GREENHOUSE GASES

The emission of energy related pollutants is a major influence of global climate alteration (IPCC, 2006, 2007). Global climate altering emissions (greenhouse gases) are usually reported in terms of carbon equivalents (IPCC, 2006, 2007). Three greenhouse gases are of primary importance when relating global climate change to energy use—carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2006, 2007). Global warming potential (GWP) is a measure of how much a given mass of greenhouse gas contributes to global climate change (IPCC, 2006, 2007). Global warming potential is calculated over a period of time and so a time-scale must be reported in order for GWP's of different processes to be meaningfully compared. Reporting greenhouse gas emissions in terms of 100-year

GWP relative to CO_2 is standard international practice (IPCC, 2007). Table 1 presents 100-yr GWP of the three greenhouse gases of primary interest. As table 1 shows, all greenhouse gases are not equal. For example 1.0 kg N_2O has the 100-yr GWP of 298.0 kg CO_2. Caculating 100-yr GWP from energy consumption is simply a matter of converting emissions of CO_2, CH_4, and N_2O into CO_2 equivalents and summing the results. Combusting 1 GJ of liquefied petroleum gas (LP gas) on farms is reported to result in emission of 63,100 g CO_2, 5.0 g CH_4, and 0.1 g N_2O per GJ of energy released (IPCC, 2006). Equation 1 presents the calculation of the 100-yr GWP of burning 1 GJ LP gas.

Equation 1

$$63{,}100\ g\ CO_2 \big/ 1\ GJ\ LP\ gas \times \frac{1\ g\ CO_2\ equivalents}{1\ g\ CO_2} = 63{,}100\ g\ CO_2\ equivalents \big/ 1\ GJ\ LP\ gas$$

$$5.0\ g\ CH4 \big/ 1\ GJ\ LP\ gas \times \frac{25\ g\ CO_2\ equivalents}{1\ g\ CH_4} = 125\ g\ CO_2\ equivalents \big/ 1\ GJ\ LP\ gas$$

$$0.1\ g\ N2O \big/ 1\ GJ\ LP\ gas \times \frac{298\ g\ CO_2\ equivalents}{1\ g\ N_2O} = 29.8\ g\ CO2\ equivalents \big/ 1\ GJ\ LP\ gas$$

$$63{,}100\ g + 125\ g + 298\ g = 63{,}523\ g\ CO_2\ equivalents/1\ GJ\ LP\ gas$$

The energy density assumptions and calculated 100-yr global warming potential of six sources of energy on Iowa farms is summarized as table 2.

CARBON

Linking greenhouse emissions with energy consumption gives rise to the notion of embodied carbon (Hammond and Jones, 2008b) and operating carbon. For example the embodied carbon of steel used in a pig building would be the greenhouse gas emissions associated with consumption of energy during production of that steel. Similarly, the operating carbon of a ventilation system in a pig barn would be the greenhouse gas emissions that result from generation of electricity to operate fans.

LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is a technique to analyze the environmental aspects and impacts associated with a product, process or service (ISO, 2006; EPA, 2008b). The main components of LCA include:

1) Inventory of all relevant energy and material inputs and environmental releases
2) Evaluation of the impacts associated with inputs and releases
(ISO, 2006; EPA, 2008b)

As the name implies LCA examines the life span of a product or service. This allows more complete accounting of the environmental impact of goods and services, but also necessitates clearly defining the beginning and end points of a product's lifespan.

There are several approaches to LCA ranging from cradle-to-gate, cradle-to-grave, and cradle-to-cradle (Hawken et al., 1999; Hammond and Jones, 2008a; Hammond and Jones, 2008b). The main difference is in the endpoint of the examined life cycle. For clarity, consider the basic example of a steel pig feeder. Cradle-to-grave LCA begins with extraction of raw materials (including recycled materials if applicable) needed to produce a product and ends with disposal of the product at the end of its use (Hammond and Jones, 2008a). Using our steel feeder example, the cycle begins with mining of iron ore and ends with eventual scrapping of the feeder after several years of use. Cradle-to-cradle LCA begins with extraction of raw materials (including recycled materials if applicable) needed to produce a product and ends with the recycling of the product into another product (Hawken et al., 1999). In this case the LCA would end with the recycling of the steel feeder into another metal product. Cradle-to-gate LCA begins with extraction of raw materials (including recycled materials if applicable) and ends with delivery of the product to its point of use. In this case the LCA would end when the feeder is delivered to a pig farm (Hammond and Jones, 2008a; Hammond and Jones, 2008b). Because of the inherent difficulties in tracking inputs and impacts after a product has been delivered to its point of use, many LCA reports are technically cradle-to-gate analyses (LaHore and Croke, 1978; Ericksson et al., 2005; Dalgaard et al., 2008; Hammond and Jones, 2008b).

LCA OF SWINE FEED INGREDIENTS

Because feed is the largest single input in swine production, the energy inputs and associated environmental impacts of swine feed ingredients have received the most attention (LaHore and Croke, 1978; Binder, 2003; Ericksson et al., 2005; Nielsen et al., 2006; Nielsen and Wenzel, 2006; Dalgaard et al., 2008). LaHore and Croke reported support energy needed to produce 19 feed ingredients for Australian pig production (LaHore and Croke, 1978). This report excludes corn and does not provide nutritional analysis of the included ingredients (LaHore and Croke, 1978).

Exogenous phytase and synthetic amino acids are an important part of consideration in modern pig production and providing those products is a multi-billion dollar business for ingredient manufacturers (Binder, 2003; Nielsen et al., 2006; Nielsen and Wenzel, 2006). Assessments of exogenous phytase have reported that the key energetic advantage of feeding phytase is reducing the amount of inorganic phosphorus in pig diets (Nielsen et al., 2006; Nielsen and Wenzel, 2006). From a pig production standpoint, it has been demonstrated that inclusion of exogenous phytase enables utilization of plant source phosphorus by pigs and allows diets containing reduced amounts of inorganic phosphorus to be nutritionally adequate

(Veum et al., 2006; Veum and Ellersieck, 2008; Emiola et al., 2009). Literature on the LCA of synthetic amino acids is less available. After an extensive search of multiple data bases, published articles, and personal communications with ingredient manufactures, only one publication presenting the production energy of synthetic amino acids could be found (Binder, 2003). Binder (2003) reports that chemical synthesis of 1.0 kg DL-methionine requires 88.0 MJ of primary energy. This value is considerably higher than the estimate of 50.0 MJ/kg for supplemental ingredients including synthetic amino acids reported by LaHore and Croke (1978). The paucity of information in the published literature pertaining to the energy required to produce L-lysine, the synthetic amino acid most commonly fed to pigs is unfortunate and should be rectified.

Production of soybean meal in Argentina with subsequent delivery to Rotterdam Habor, in the Netherlands has been reported (Dalgaard et al., 2008). Imported soybean meal is a major source of amino acids for pigs in Europe (Ericksson et al., 2005; Dalgaard et al., 2008). The application of information presented by Dalgaard et al. (2008) to Iowa swine production must take into account the likelihood of substantial reductions in transportation energy required. Dalgaard et al. (2008) estimate an ocean voyage of more than 12,000 km for soybean meal from Argentina to the Netherlands. Given Iowa's leadership in U. S. soybean production (USDA, 2009) and processing (Hardy, 2009), it is reasonable to assume that soybean meal fed in Iowa travels a much shorter distance.

ASSESSMENT OF PIG PRODUCTION INPUTS AND IMPACTS

Iowa pig production in 1975 was estimated to require input of 2,622 MJ non-solar energy per 100 kg of liveweight (Reid et al., 1980). Approximately 65% of the energy input was directly associated with swine feed (Reid et al., 1980). For every 100 kg of pigs produced 809 m^2 of cropland was required (Reid et al., 1980). United States pig production has changed dramatically since 1975, but Reid et al (1980) provides a historic perspective of Iowa pig production.

The efficiency of Swedish pork production reportedly increased by approximately 20% between the years 1972 and 1993 (Uhlin, 1998). Feed and fertilizers accounted for 60% of the energy input in Swedish pork production in 1993 (Uhlin, 1998). Uhlin (1998) reported the total energy use for pig production relative to energy output in pork. This is a unique reporting strategy among the LCA literature pertaining to pig production. The researchers reported that in 1993, Swedish pork required 4.10 MJ non-solar energy input for every 1.0 MJ of pork produced (Uhlin, 1998). The energy density of fresh pork carcass, excluding bone and skin is reported as 15.73 MJ/kg (USDA, 2008). Assuming a reported dressing percentage of 72% for pigs (Lammers et al., 2008), the non-solar energy input is calculated to be 46.4 MJ/kg live weight.

Indicators of resource use and environmental impact for 5 pig farms in Denmark were collected for 3 years (1994–1997) (Halberg, 1999). The selected farms did not statistically represent Danish farms, but they were typical pig farms for Denmark at that time (Halberg, 1999). Non-solar energy inputs of 13–20 MJ per 1.0 kg of live weight was reported with no examination of the portion of non-solar energy committed to feed production presented (Halberg, 1999).

Dutch researchers compared pork with pea-based protein for human nutrition and assumed 3,783 MJ of non-solar energy input for every 112.2 kg pig (Zhu and van Ierland, 2004). The researchers included energy use for growing crops, manufacturing feed, pig farming, harvest of the animal, and processing of meat products (Zhu and van Ierland, 2004).

Although their precise methodology is opaque, it is estimated that Zhu and van Ierland (2004) attributed 70% of the total non-solar energy input to producing the pig or 2,650 MJ per 112.2 kg live pig. A total of 741.7 kg of CO_2 equivalents were attributed to each pig through the entire pork chain (Zhu and van Ierland, 2004). Because greenhouse gas emissions are closely tied to energy consumption, it is estimated that 70% of the total CO_2 equivalents (519 kg) were allocated to producing the 112.2 kg market pig.

The estimated non-solar energy use for pig production under different production schemes in France ranges from 15.9–22.2 MJ per kg of pig (Basset-Mens and van der Werf, 2005). The scenario most closely resembling commodity pork production in the United States required 15.9 MJ of non-solar energy input and resulted in emission of 2.3 kg CO_2 equivalents per 1.0 kg of pig live weight (Basset-Mens and van der Werf, 2005). The French researchers estimated 2.7% of total non-solar energy use should be attributed to operation of pig housing with 74% of the non-solar energy use being associated with crop and feed production (Basset-Mens and van der Werf, 2005).

Researchers in Sweden focused on the impact of feed choice on energy use and environmental impacts of pork production (Ericksson et al., 2005). Three scenarios for protein supply were considered—imported soybean meal, locally produced peas and rapeseed cake, and locally produced peas and rapeseed cake with synthetic amino acids (Ericksson et al., 2005). Their analysis assumed soybean meal was imported from South America, this resulted in the pigs fed soybean meal based diets requiring 6.8 MJ non-solar energy input/kg pig growth (Ericksson et al., 2005). Pigs fed locally sourced peas and rapeseed cake required the least non-energy input, 5.3 MJ/kg growth (Ericksson et al., 2005). Adding synthetic amino acids to locally sourced peas and rapeseed cake dramatically reduced predicted nitrogen excretion by the growing pigs, but resulted in use of 6.3 MJ non-solar energy per kg of pig growth (Ericksson et al., 2005). The researchers focused exclusively on the grow-finish stage of production and did not include energy use or environmental impacts resulting from operation of pig housing (Ericksson et al., 2005). The three dietary scenarios resulted in emission of 1.5, 1.3, and 1.4 kg CO_2 equivalents/kg of pig growth (Ericksson et al., 2005).

A 2006 United Kingdom report estimated the non-solar energy use for 1.0 kg of pork as 17.0 MJ and the 100-yr GWP as 6.4 kg CO2 equivalents (Williams et al., 2006). The purpose of this report was to compare many different commodities with each other rather than methods for producing one particular product (Williams et al., 2006). Energy use for building operation was not reported and no comparisons of different types of pig farms were made (Williams et al., 2006).

Belgium researchers used a Flemish farm database of technical and economic records to establish a representative specialized pig farm for modeling purposes (Meul et al., 2007). They used this model farm to estimate energy use efficiency for different farm types using process analysis methodology (Meul et al., 2007). This method calculates direct and indirect energy inputs based on physical material flows and ignores solar energy and human labor inputs (Jones, 1989). Although inclusion of human labor inputs would result in a more complete evaluation of agricultural systems the difficulty in quantifying and allocating human labor and the corresponding introduction of error into the analysis is generally considered to outweigh the potential benefits (Jones, 1989). Meul et al. (2007) considered energy input using the cradle-to-gate approach of LCA. They included embodied energy use one step backwards from the farm—i.e. energy used to produce fertilizers was included, energy used to manufacture the fertilizer plant was not (Meul et al., 2007). Non-solar energy use of 17.2 MJ/kg carcass weight was reported for the average pig farm model with 70% of the non-solar energy use being directly attributed to feed production (Meul et al., 2007). The researchers also generated a model representing the 5% most energy efficient pig farms and examined energy use for those operations (Meul et al., 2007). It is estimated that the most energy efficient pig farms require10.6 MJ of non-solar energy use/kg carcass weight with 73% of non-solar energy use directly attributed to feed (Meul et al., 2007).

The most recent assessment of swine production was conducted in Denmark and focuses exclusively on global warming, eutrophication, acidification, and photochemical smog (Dalgaard et al., 2007). Resource use for grain, soybean meal, heat, and electricity are stated and can be used to calculate non-solar energy consumption. If a barley-soybean meal diet is assumed total non-solar energy inputs are 43.34 MJ/kg pork (Dalgaard et al., 2007). This assumes a gross energy (GE) value for barley and soybean meal of 15.9 and 17.2 MJ/kg respectively (Sauvant et al., 2004). Valuing feed inputs based on GE is problematic from a nutritional standpoint, but is the most straightforward method to derive a non-solar energy input estimate from the provided information. For every 1.0 kg pork produced under the conditions of the Danish model, emission of 3.6 kg CO_2 equivalents occurs (Sauvant et al., 2004).

Table 3 summarizes nine reports of energy use and CO_2 emissions for pork production. Recent work in this area has focused in Europe and Denmark in particular. There are fundamental differences between European and United State pigs production that limits the application of European results to inform decision making by pig producers in Iowa. European swine diets typically include more variety in feed ingredients and often include high amounts of small grains such as barley. Peas, rapeseed cake, and soybean meal are all commonly used as protein sources in European swine diets. Iowa swine diets are almost entirely comprised of corn and soybean meal. Pigs are generally limit fed in Europe and fed ad libitum Iowa. Diet form may also vary. Feeding pelleted or liquid feeds in Europe is common while in the United States almost all diets are fed as dry mash. Some Iowa farms do provide water at the feeder, encouraging consumption of a wet-dry feed, but this strategy is very different from liquid feeding systems seen in Europe. Market weight in the United States is also heavier than in Europe. Finally climate conditions and primary environmental concerns are different between Europe and Iowa.

ENERGY IN PIG NUTRITION

Approximately 60-80% of the total cost of pork production can be attributed to providing feed to the animal (Fowler, 2007). And energy components account for 80-90% of pig diets by mass (Holden et al., 1996). Historically highly digestible starches have been the primary source of energy in pig diets with fats and oils playing an important role particularly in diets for young pigs. Forages and nonstarch polysaccharides are of limited use in modern growing pig diets although these feedstuffs can be fed to pregnant sows without negative effects on reproductive performance (Calvert et al., 1985; van der Peet-Schwering et al., 2002). Proteins can be catabolized by the pig. Proteins are less energy dense than lipids and have an energy density that is similar to carbohydrates (Berg et al., 2002; Salway, 2004). Catabolism of proteins requires elimination of nitrogen from the body, an activity that lowers the net gain in biologically useful energy from oxidation of proteins relative to carbohydrates and lipids (Berg et al., 2002; Salway, 2004). Traditionally the price premium paid for proteinaceous feedstuffs has been too high for widespread use of protein as a source of energy for pigs.

Gross energy (GE) is the theoretical maximum energy that could be used by the pigs and is defined as the energy releases as heat following total combustion of a feedstuff (NRC, 1998; Ewan, 2001). Although GE is the starting point for further calculations, it is not a good measure of useful energy for pigs because it does not consider any of the losses of energy during ingestion, digestion, and metabolism of a feedstuff (Moehn et al., 2005). For example 1.0 kg of starch has approximately the same amount of GE as 1.0 kg of straw (Moehn et al., 2005) and 1.0 kg of corn has similar GE as 1.0 kg of soybean hulls (Sauvant et al., 2004).

Terms commonly used to describe dietary energy include DE, ME, and NE (Ewan, 2001; Moehn et al., 2005). Digestible energy (DE) is the GE of the feed consumed minus the GE of the feces excreted (NRC, 1998; Ewan, 2001; Moehn et al., 2005). Metabolizable energy (ME) is DE minus energy excreted in urine and combustible gases (NRC, 1998; Ewan, 2001; Moehn et al., 2005). While DE and ME are relatively simple to determine, they only express potential energy and do not take into consideration the pig's ability to utilize energy from different dietary sources (Moehn et al., 2005; Noblet, 2006, 2007). Given work demonstrating pigs utilize energy present in consumed starch, protein, and lipid at different efficiencies (van Milgen et al., 2001), DE and ME values for feedstuffs are limited. The practical effect of using DE and ME systems is that they typically overestimate the energy value of protein and underestimate the energy value of lipids (Noblet, 2007; Payne and Zijlstra, 2007).

Net energy (NE) values of feedstuffs provide a more precise measure of the energy available for use by the animal (Ewan, 2001; Moehn et al., 2005; Noblet, 2007). Net energy is defined as ME minus the heat produced during digestion of feed, metabolism of nutrients, and excretion of wastes (Ewan, 2001; Moehn et al., 2005). The energy left following those losses—energy in feces, urine, and gaseous products of digestion, and heat produced during digestion, metabolism, and excretion—is the energy actually used by the animal for maintenance and production (Moehn et al., 2005; Noblet, 2006, 2007). Net energy is thus the only system that expresses usable dietary energy by incorporating the efficiency of nutrient use. Most North American swine nutritionists are most familiar with DE and ME systems. Although DE or ME systems may have been sufficient when formulating simple diets containing primarily corn and soybean meal, the advantages of the NE system are greater as diet complexity increases. Discussion surrounding adoption and application of a net energy system is on-going among North American swine nutritionists (Moehn et al., 2005 ; Payne and Zijlstra, 2007; Zijlstra and Payne, 2008).

As noted by Payne and Zijlstra (2007) the efficacy of any energy system is dependent upon the accuracy of the energy values assigned to a set of ingredients. The DE, ME, and NE values of many ingredients can be readily obtained from feeding tables (NRC, 1998; Sauvant et al., 2004) but use of those values are only appropriate for ingredients having chemical characteristics similar to those in the tables (Noblet, 2007). As feed ingredients become increasingly differentiated—DDGS from one particular ethanol plant, soybean meal from low linolenic acid soybeans, low phytate corn—the task of updating ingredient nutrient matrices to reflect the feed ingredient actually used becomes critical. Payne and Zijlstra (2007) provide an action plan for analyzing ingredients, calculating values, and adjusting formulation schemes accordingly. Equations for calculating NE from chemical analysis of crude protein, fat, and fiber; moisture; ash; acid and neutral detergent fiber; sugar; and starch were proposed by Noblet et al. (1994). These equations are the basis for the energy values reported by Sauvant et a. (2004). The most recent NRC for swine presents NE values based on the work of several different researchers (NRC, 1998) and in general NE values reported by NRC are lower than those explicitly calculated by Sauvant et al. (2004).

AMINO ACIDS

Growing pigs fed grain-based diets typical of modern swine production eat to satisfy a demand for energy and so the quantity of feed consumed depends on the energy density of the diet fed (NRC, 1998; Ellis and Augspurger, 2001; Ewan, 2001; Whittemore et al., 2003). Nutrient-to-energy ratios are thus important considerations when formulating and comparing pig diets (NRC, 1998; Ellis and Augspurger, 2001; Ewan, 2001; Whittemore et al., 2003). It is well established that different amino acids are required in different proportions to support growth of pigs (Lewis, 2001) and current nutrient recommendations relate intake of the essential amino acids in proportion to intake of lysine (NRC, 1998; Whittemore et al., 2003). The amino acid present in the least amount relative to the pig's requirement is known as the first limiting amino acid (Lewis, 2001; Whittemore, 2006). Lysine is generally the first limiting amino acid in practical swine diets with methionine, threonine, and tryptophan also being of key concern (Lewis, 2001).

SWINE NUTRITION RECOMMENDATIONS

Nutrition recommendations for swine in the United States are currently based on metabolizable energy and apparent ileal digestible amino acids (NRC, 1998). A net energy (NE) system considers the amount of heat lost during digestion and subsequent deposition of nutrients in body tissue and is thus a more accurate estimate of the true energy content of an ingredient (Ewan, 2001; Moehn et al., 2005; Noblet, 2007). Discussion of the practicality and application of a net energy system is on-going among North American swine nutritionists (Moehn et al., 2005 ; Payne and Zijlstra, 2007; Zijlstra and Payne, 2008). At present standardized ileal digestibility is the most accurate basis for diet formulations in regards to amino acids availability (Gabert et al., 2001; Sauvant et al., 2004; Stein et al., 2007a; Stein et al., 2007b). More recent European recommendations are based on net energy and standardized ileal digestible amino acids (Whittemore et al., 2003). Feedstuff tables presenting the NE and SID amino acid content of feed ingredients are available (Whittemore et al., 2003; Sauvant et al., 2004).

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Table 1. One hundred year global warming potential of three primary greenhouse gases[a]

Common name	Chemical Formula	100-yr GWP, CO_2 equivalents
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298

[a] (IPCC, 2007)

Table 2. Energy density and 100-yr global warming potential of common Iowa farm fuels

Fuel	Energy density, MJ/L	100-yr GWP, g CO_2/MJ
Corn grain	11.7[a]	na
Liquefied petroleum gas	25.73[b]	63.52[c]
Number 2 diesel	38.46[b]	82.73[c]
Electricity	na	229.32[d]
Ethanol	21.3[e]	na
Biodiesel	34.5[f]	na

[a] Gross energy of corn grain is 16.2 MJ/kg (Sauvant et al., 2004)
[b] (Downs and Hansen, 1998).
[c] (IPCC, 2006).
[d] Calculated from weighted average of fuels consumed for electricity generation and transmission losses for Iowa (IPCC, 2006; EPA, 2008a)
[e] (Hill et al., 2006).
[f] (Hill et al., 2006; Huo et al., 2008)

Table 3. Summary of published energy assessments of pig production[a]

Location	Production Year	Non-solar energy input, MJ/kg live wt.	Non-solar energy attributed to feed, % of total	Emissions, kg CO_2 equivalents/ kg live wt.
Iowa[b]	1975	36.2	72.2	nr
United States[b]	1975	37.2	71.7	nr
Sweden[c]	1993	46.4	61.0	nr
Denmark[d]	1997	17.0	NR	nr
Belgium[e]	1998	23.7	70.0	nr
Belgium[f]	1998	14.6	73.0	nr
Denmark[g]	2004	23.6	NR	4.6
France[h]	2005	15.9	74.0	2.3
Denmark[i]	2005	6.8	100.0	1.5
Denmark[j]	2005	5.3	100.0	1.3
Denmark[k]	2005	6.3	100.0	1.4
United Kingdom[l]	2006	23.5	nr	8.8
Denmark[m]	2007	59.8	nr	5.0

[a] Assumes 1 kg of pork = 1.38 live weight
[b] (Reid et al., 1980)
[c] (Uhlin, 1998)
[d] (Halberg, 1999)
[e] Average farm examined (Meul et al., 2007).
[f] Top 5% energy efficient pig farms in database (Meul et al., 2007).
[g] (Zhu and van Ierland, 2004)
[h] (Basset-Mens and van der Werf, 2005)
[i] Imported soybean meal as protein source, finishing phase only (Ericksson et al., 2005).
[j] Local pea and rapeseed meal as protein source, finishing phase only (Ericksson et al., 2005).
[k] Local pea and rapesedd meal with synthetic amino acids, finishing phase only (Ericksson et al., 2005).
[l] (Williams et al., 2006)
[m] Calculated based on gross energy of barley-soybean meal diet (Dalgaard et al., 2007).

CHAPTER 3. CONSTRUCTION RESOURCE USE OF TWO DIFFERENT TYPES AND SCALES OF IOWA SWINE PRODUCTION FACILITIES

A paper accepted by *Applied Engineering in Agriculture*

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ABSTRACT. As global populations and affluence rise, there is increasing demand for energy, animal protein, and construction materials. In many cases, available resource pools are insufficient to meet growing market demands, resulting in increased prices and competition for limited resources. This study evaluates key construction resources needed to build different types and scales of Iowa swine production facilities. Two types of facilities—conventional confinement and hoop barn-based—within farrow-to-finish pig production systems scaled to produce either 5,200 or 15,600 market pigs annually are examined. Conventional confinement facilities are typical of pork industry practice in the United States and are characterized by individual gestation stalls and 1,200 head grow-finish buildings with slatted concrete floors and liquid manure systems. The hoop barn-based alternative uses bedded group pens in hoop barns for gestation and finishing. Five building materials: concrete, steel, lumber, thermoplastics, insulation, as well as crushed rock and diesel fuel used for building site preparation are considered. Land surface area required for buildings

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and pig production infrastructure are also compared. Relative market costs of newly constructed swine facilities are compared under several material price scenarios. Using hoop barns for grow-finish and gestation results in lower construction costs. Increasing the scale of pig production results in lower construction costs per pig space, however the construction costs per pig space for a 5,200 head hoop barn-based complex is less than the construction costs per pig space for a 15,600 head conventional confinement system. In terms of construction resource use and cost, hoop barns for swine are a viable alternative that are less dependent on the scale of production than conventional confinement facilities.

Keywords. Building materials, Construction costs, Hoop barn, Swine production.

INTRODUCTION

Global population is projected to reach 9.2 billion people in 2050 and if realized will represent an increase of more than 360% over a 100 year time period (UN, 2007). Population in China and the United States is also projected to increase dramatically (UN, 2007). Those two countries lead the world in pork production and consumption, a trend that is likely to continue (den Hartog, 2005; FAO, 2006). Increased population and rising incomes have created increased market demand for energy, animal protein, and construction materials globally. Over time, increased market demand for available resources typically results in greater price competition for those resources. Thus it is appropriate to examine the relative efficacy of using construction resources to build different types and scales of animal protein production systems. This paper examines the material use for constructing different types and scales of Iowa swine production facilities. Relative costs of building different types and scales of Iowa swine production facilities are also compared under different pricing scenarios. Information presented in this paper constitutes an inventory of construction resources required for construction of pig production facilities. This inventory can be combined with additional information to conduct a life cycle analysis of pig production, however the present paper is not a complete life cycle analysis of pig production facilities.

METHODS

This project considers input of construction resources into different types and scales of swine production facilities based upon physical material flows. Two types of facilities—conventional confinement and hoop barn-based are considered within identically scaled farrow-to-finish production systems. The conventional confinement system is typical of pork industry practice in Iowa and is characterized by individual gestation stalls and 1,200 head grow-finish buildings with slatted concrete floors and liquid manure systems. The hoop barn-based alternative system uses group pens in bedded hoop barns for gestation and finishing. Both systems will use farrowing crates and climate controlled nursery facilities and are summarized in table 1. Resource use is related to volume of pig flow and so pig production systems sized to produce batches of either 400 or 1,200 pigs every 28 d, or 5,200 and 15,600 pigs annually are compared.

PIG FLOW REQUIREMENTS

PigCHAMP is a production record system widely used in the United States pork industry and summarized records of reproduction performance are available online (PigCHAMP, 2008). Average reproductive performance benchmarks for PigCHAMP users in 2004 and 2006 were used to calculate pig numbers and flow through breeding, gestation, and farrowing. The latest USDA survey of pig producers in the U.S. (USDA, 2007) reports days spent in a particular housing type as well as mortality rates during a specific growth phase. This information was used to calculate pig numbers and flow through nursery and grow-finish facilities. Pig flow parameters used to calculate space requirements are detailed in table 2. Table 3 details pig space needs for annual production at the level of 5,200 and 15,600 market pigs annually. The hoop-based system will require the same type and number of pig spaces as the conventional confinement system, although spaces will be distributed across more individual buildings.

BUILDING MATERIALS

The buildings examined are simplified design models that were generated to provide estimates of building material use. Building dimensions, layout, and material selection decisions for the examined facilities were determined by interviewing construction firms, facility managers, and industry consultants. Although the buildings are intended to be similar to actual facilities currently being built in Iowa they are not engineered designs. Application of the buildings or building components described should be limited to estimating material use of similar buildings. Midwest Plan Service publications (MWPS, 1987, 1989a, b; Brumm et al., 2004; Harmon et al., 2004; Koenig and Runestad, 2005) were used as a basis for all designs. Table 4 provides a basic summary of building dimensions and layout. The farrowing facility used by conventional confinement system and the hoop barn-based system is identical in terms of size and room set-up. Both systems also use a pull-plug manure system. However, in the conventional confinement system the pull-plug manure system is connected through underground pipe to the gestation barn's 2.4 m deep manure storage tank. This is typical of conventional confinement facilities in the U.S. In the hoop barn-based system, the gestation facilities are hoop barns and do not have pits for liquid manure storage. Thus in the hoop barn-based system, farrowing facilities must include a 2.4 m deep pit appropriately sized for liquid manure storage from the farrowing facility. For this comparison the hoop barn-based system's farrowing facility includes an exterior pit. The hoop barn-based farrowing pit in this analysis is a 3.6 m wide, 2.4 m deep pit that runs the length of the building (21.9 m long for the 5,200 market pig system and 73.2 m long for the 15,600 market pig system).

Farrowing and nursery facilities consist of a 2.4 m high, framed wall around the entire building. The exterior wall is sheeted with steel while the wall that is in contact with the pigs is covered with commercially available high-density polyethylene sheeting. Appropriately designed wood rafters sit on top of the walls. Steel sheeting is assumed for the roof and ceiling of farrowing and nursery facilities.

The building shell for breeding and gestation and grow-finish within a facility type are similar. The conventional system begins with a 2.4 m deep pit and concrete slats. On top of the pit wall a 1.4 m high concrete sidewall is poured around the entire building. A 0.9 m high framed wall is set on top of the concrete walls. The buildings described are rectangles, the short sides of the rectangles are enclosed with exterior steel and interior high-density polyethelene sheeting. The long walls of the buildings are covered by a 0.9 m tall curtain that runs the length of the building. Above the curtain a 0.3 m header is assumed with appropriately designed lumber rafters sitting on top of the building wall. Steel sheeting is assumed to cover the roof and ceiling in conventional grow-finish and gestation facilities.

Hoop structures for swine are less complex in their construction. A hoop barn is a Quonset™-shaped structure that has been previously described (Honeyman et al., 2001; Brumm et al., 2004; Harmon et al., 2004). Hoop barn sidewalls are assumed to be 1.5 m high and consist of wooden posts and sidewalls. Tubular steel arches are attached to the posts, forming a hooped roof. A UV resistant, high-density polyethylene tarp is pulled over the arches and fastened to the sidewalls. It is assumed that the entire floor area is covered with reinforced concrete. Hoop barns for grow finish have a 0.8 m high elevated pad covering 1/3 of the floor area. Feeders and waterers are located on this pad. In hoop barns for gestation a 3.0 m wide 0.8 m high pad is set along one of the long side-walls with feed stalls located on top of the concrete pad. An appropriate waterer is located on the other side of the building on top of a small (1.8 × 0.9 m), 0.8 m high concrete platform.

Five primary building materials are reported: concrete, steel, lumber, insulation, and thermoplastics. Each material is not a homogenous entity, but for this comparison material specifications have been standardized and material use is reported by mass. For this comparison, the volume of each material was calculated from a list of materials for every building and then multiplied by a density factor appropriate for each material. Table 5 presents material density assumptions used to calculate mass of materials required for a particular building. Current prices of building materials were collected by personal interview with various suppliers operating in Iowa, the leading pig producing state in the U.S. The estimated market values of construction materials are summarized in table 5.

LAND SURFACE AREA

Multi-site pig production is common in the United States, however for this comparison it is assumed that one building site is used for all phases of production. Individual buildings detailed in Table 4 were arranged on a scaled model site according to the following guidelines. First, a distance of at least 46 m was maintained between distinct phases of production—farrowing, nursery, grow-finish, and gestation. Secondly a minimum of 6 m distance was maintained between individual buildings within a production phase—

between grow-finish barns for example. Finally, a 6 m buffer was added to the edge of all buildings lining the perimeter of the building site. For the hoop barn-based building sites, storage hoops for bedding were positioned near the gestation and grow-finish hoop barns. Hoop barns used for storage were allowed a 6 m separation between other buildings, but were not required to be separated by 46 m from buildings housing pigs. Access roads to facilities were then outlined on the scaled model. A perimeter was drawn around the entire building site to delineate total land surface area needed for buildings, access roads, and buffers. The market value of land suitable for building swine facility complexes was assumed to be $3,200/ha for initial analysis.

BUILDING SITE PREPARATION

It was assumed that the building site was previously furnished with sufficiently sized wells, electrical mains, and a main entrance driveway. Building site preparation includes excavating manure storage pits, backfilling completed manure storage pits, grading the entire building site, and building access roads. Earthwork for nursery, conventional gestation, and conventional grow-finish buildings was calculated by multiplying the building dimensions by the depth of the manure storage pit. The building dimensions and manure storage pit depths given in table 4 were increased by 0.5 m and then used to calculate volume of soil to be excavated. The volume of backfill required for each building was calculated by subtracting the volume of the manure storage pit from the volume excavated. Grading of the building site was calculated by multiplying the site’s entire surface area by 0.3 m and is used to estimate the earthwork needed to reposition soil that was excavated in excess of the backfill for manure pits, as well as prepare the building site for farrowing facilities and hoop barn construction. In the conventional confinement system, manure from the farrowing facility is stored in the gestation barn pit and no additional earthwork was included in the estimate. The farrowing facility used in the hoop barn-based systems has a manure storage pit and so excavation and backfilling was calculated for a 2.4 m deep manure storage pit adjacent to the farrowing facility. Access roads were calculated by multiplying the length of each road by a width of 3 m and a depth of 0.9 m. Each access road was finished by covering with a 0.3 m thick layer of crushed rock.

Appropriately sized machines were selected for earthwork based on discussions with equipment company representatives. The time required to complete each task was calculated using machine capacities and construction estimating references (RES, 1990; Mossman and Plotner, 2006). Hours of operation were then multiplied by fuel use per hour values presented by Caterpillar Inc. (2008). Initial costs analyses assume diesel fuel is valued at $1.00/l.

LABOR AND MATERIAL COSTS

Labor and material costs were first calculated for each building based on the material list for each building and data presented by Mossman and Plotner (2006). Prices reported by Mossman and Plotner (2006) represent the estimated national average for industrial and commercial construction projects. National averages can be indexed for different locations providing a more precise cost estimate. Because costs for Iowa under most labor and material divisions relevant to construction of swine facilities were below the national average (Mossman and Plotner, 2006), national averages are reported. Labor and material costs are highly dependent on specific activities, for example the labor cost of excavating a cubic meter of soil is nearly twice the labor costs of grading the same volume of soil (Mossman and Plotner, 2006). The reported comparisons used task specific labor and material costs to calculate total project costs.

CONSTRUCTION COST SENSITIVITY TO PRICE CHANGE

The sensitivity of the total construction cost for a given type and scale of swine facilities to changes in prices of concrete, steel, land, labor and energy were examined. Sensitivity analysis for concrete, steel, land, and labor was performed by multiplying the reported cost associated with each resource by price increases of different magnitudes and then adding the additional cost to the original construction costs. Sensitivity analysis for energy costs increases required calculating the impact of energy prices on all resources. Embodied energy is the energy used to generate a particular material. Hammond and Jones (2008) details the embodied energy of building materials from cradle-to-gate. In other words the embodied energy values used in our analysis account for energy required to gather and process raw and recycled materials into construction resources but does not consider the energy associated with a construction material after it has been produced. There is no universally accepted value of the embodied energy of a specific material, but using a readily available reference that includes all examined materials (Hammond and Jones, 2008) ensures that materials are compared on an even basis. Two building resources considered, diesel fuel and thermoplastics, are almost entirely composed of petroleum and thus are very dependent on the price of energy. The relative magnitude of embodied energy of concrete, steel, lumber, and insulation relative to thermoplastics is 0.01, 0.32, 0.10, and 0.03. For example if a given mass of thermoplastic has an embodied energy value of 100 MJ, the embodied energy values of equivalent masses of concrete, steel, lumber, and insulation would be 1, 31, 10, and 3 MJ, respectively. If all energy prices increase by 25%, the price of thermoplastics and diesel fuel are assumed to also increase by 25%. The market price of concrete, steel, lumber, and insulation are assumed to increase proportionally to their embodied energy value relative to thermoplastics.

RESULTS

Table 6 presents construction resource use for swine production facilities. Increasing the number of pigs sold annually resulted in increased use of construction resources. However in most cases tripling pig production space increased construction resource use by less than 300%. There was little overall difference in the magnitude of resource use between the two scales of pig production within a facility type. More land area is necessary to site the hoop barn-based systems, but fuel use to perform earthwork operations is half of what conventional confinement facilities require. Generally fewer building resources were required for the hoop barn-based systems.

Estimated construction costs for swine production facilities based on Mossman and Plotner (2006) are summarized in table 7. The farrowing facility for the hoop barn-based system includes a 2.4 m manure storage pit, while in the conventional confinement system manure from the farrowing facility is stored in the gestation pit. This difference results in the farrowing facility for the hoop-based systems costing 11–14% more than the farrowing facility for the conventional confinement systems. The major difference between the hoop barn-based system and the conventional confinement system is the cost of building grow-finish facilities. Estimated construction costs of hoop barns for grow-finish pigs are 27–41% of the construction costs of similarly sized conventional facilities. Estimated gestation facility costs are below previous estimates (Lammers et al., 2008), however the current estimate does not include ventilation or water systems. Building hoop barn-based gestation is estimated to cost 31–64% less than conventional confinement facilities with the major differences from less concrete and steel being used in the hoop barns. Both systems include individual gestation stalls and gestation stalls are a significant contributor to the total mass of steel in both types of facilities. Although stalls used for feeding are not as heavy as stalls used for gestation, this analysis assumes gestation stalls are used for housing gestating sows in the conventional confinement system and for feeding gestating sows in the hoop barn-based system. The hoop barn-based system requires storage facilities for bedding as well as more land, crushed rock, labor, and equipment use for site preparation. Still this greater use of resources did not negate the cost advantages presented by using hoop barns for grow-finish and gestation.

The estimated construction cost per market pig space is very different for the two systems. Estimated construction costs per pig space are lowest for the 15,600 head hoop barn-based complex and both hoop barn-based systems cost less per pig space than any conventional confinement system considered. Increasing the size of the operation resulted in lower construction costs per pig space. Moving from 5,200 head to 15,600 head in the conventional confinement system results in a construction cost reduction of 38% per pig space. In the hoop barn-based system the same change in size only reduces construction costs by 13% per pig space. Labor costs are highly dependant upon type of activity. Building conventional confinement facilities and hoop barn-based facilities require different amounts of different types of labor. This is illustrated by the reported differences in reduction of building cost per pig space between conventional confinement and hoop barn-based systems.

Labor and material costs were also estimated for each swine facility complex using mass and market values of materials reported in tables 5 and 6. Hours of labor were estimated based on Mossman and Plotner (2006). An initial value of $20/hr was assumed for all construction labor. Table 8 presents estimated construction costs for swine facility complexes based on material use calculations. Overall costs estimated based on material mass is less than costs estimated according to Mossman and Plotner (2006). Costs presented by Mossman and Plotner (2006) are national averages, while costs used in the material mass method are more accurate for Iowa. The cost of building swine facilities on a market pig space basis follows a similar pattern regardless of the method of estimation. Based on material mass the cost per pig space for a hoop barn-based facility sized to produce 15,600 pigs is $92, while the hoop barn-based facility producing 5,200 pigs annually can be built for a cost of $107/pig space. Both are lower than the costs of building a 15,600 head conventional confinement facility which in turn is less than the construction cost of a 5,200 head conventional confinement facility. In the conventional confinement system, increasing size from 5,200 head to 15,600 head results in reducing construction costs by 25%. In the hoop barn-based system increasing the size of facilities from 5,200 head to 15,600 head results in a 14% reduction in construction costs.

Actual building costs are likely to be different than the estimates presented in tables 7 and 8. However, it is expected that the distribution of costs within a facility type and the magnitude of differences between conventional confinement facilities and hoop barn-based systems remain relatively constant. For example, approximately 70% of the costs of building swine facilities are material costs with the remainder being allocated to labor costs. Systems that use bedded hoop barns for gestation and grow-finish cost less to construct than conventional confinement facilities for identically scaled operations. Increasing the total volume of pigs produced results in reduced construction cost per pig space, however the hoop barn-based system producing 5,200 pigs annually costs less to construct per pig space than the conventional confinement facilities producing 15,600 pigs annually regardless of the method used to estimate construction costs.

Results from table 8 were used to compare the effect of construction resource price changes on the total costs of different types and scales of pig facilities. Construction cost sensitivity to changes in the value of concrete and steel are presented as figures 1 and 2. More concrete and steel per pig space are used in the conventional confinement facilities. Increasing the cost of concrete and steel increases the construction costs for all type and scales of pig facilities. If resource prices change uniformly for all types and scales of pig production facilities, the construction costs per market pig sold for a conventional confinement facility sized to produce 15,600 market pigs annually is very similar the construction costs per market pig sold for a hoop barn-based system producing 5,200 market pigs annually. If concrete or steel prices increase by 25%, construction costs per market pig sold increase by 3–4% or 4–5% respectively. Doubling the price of concrete increases construction costs per market pig sold by 15–18%. A doubling in the price of steel results in a 21–25% construction cost per market pig sold increase. Even if resource prices do not change uniformly for all types and scales of pig production facilities it is only at the extremes that the generalized cost advantage of building hoop barn-based systems sized to produce 15,600 market pigs annually do not hold. For example if a firm building the hoop barn-based system sized to produce 15,600 market pigs annually pays double the price for steel that a construction firm building the conventional confinement facilities sized to produce 15,600 market pigs annually can obtain, then construction costs for the conventional confinement facility are approximately 1% less than the construction costs for the hoop barn-based system.

Pig production in hoop barns allows more space per pig, but does require more land surface area. Figure 3 details construction cost sensitivity to changes in land values. Because the cost of land is a relatively small factor in the total construction cost of a pig facility, construction costs are not very responsive to land value increases. A doubling of land values only increases the total construction costs per market pig sold by 3–8% regardless of type and scale of facility. The construction costs of hoop barn-based systems are more sensitive to land value changes than in conventional confinement. However land values would have to increase more than 2,000% (data not shown) before conventional confinement facilities have a construction cost advantage over hoop barn-based systems due to land costs.

Labor is the single largest construction expense in building pig facilities. Figure 4 details the effect changing labor values have on the total construction costs of different types and scales of pig production facilities. Increasing the size of the production facilities delivers construction cost per market pig sold advantages. In the conventional confinement system construction costs per market pig sold for the facilities sized to produce 5,200 market pigs annually are 33–41% higher than construction costs per market pig sold for the facilities sized to produce 15,600 market pig under the different labor value scenarios. The hoop barn-based system construction costs per market pig sold for facilities sized to produce 5,200 market pigs annually are only 13–16% higher than the construction costs per market pig sold for the facilities sized to produce 15,600 market pig annually. The firm building hoop barn-based systems at the 15,600 market pigs per year scale would have to pay approximately 40% more for labor than the firm building conventional confinement facilities at the 15,600 market pigs per year scale before construction costs are higher for the hoop barn-based system.

The effect of changing energy prices on the total construction costs of different types and scales of pig production facilities are presented as figure 5. Systemic increases in the price of energy has more dramatic impact on the relative construction cost per market pig at the 10% level than other resource price increases. Increasing energy prices by 10% results in a 7–8% increase in construction costs for all facility types and scales. Increasing energy prices by 25% results in a 8–10% increase in total construction costs from initial conditions. Energy price increases ranging between 10 and 75% result in total construction costs increasing linearly at rate of 6–8%. Doubling the value of energy resources causes a spike in total construction costs. Doubling the value of energy resources increases the construction costs of the examined pig production facilities by 26–31%.

Based on construction costs per market pig sold, there is more incentive to increase the scale of pig production in conventional confinement systems than in hoop barn-based systems. For all construction resource price scenarios examined the difference between the 5,200 and 15,600 market pig firms was greater for the conventional facilities than the hoop barn-based systems. If all firms have access to construction resources at the same price, construction cost per market pig sold for a hoop barn-based production facility sized to produce 5,200 market pigs annually is less than the construction costs per market pig sold for a conventional confinement facility producing 15,600 market pigs annually. Firms that are building facilities on a larger scale may be able to achieve some resource pricing advantages over smaller firms. However, it is unlikely that a conventional confinement swine facility sized to produce 15,600 pigs annually would have more negotiating clout than a hoop barn-based swine facility producing the same number of pigs.

CONCLUSIONS

This paper examines construction resources of different types and scales of Iowa swine production facilities. The environmental impact of pig production also depends on production efficiency of different systems, energy use by those systems, resulting emissions, and nutrient cycling within a production system. The present comparison of construction resource use does not provide a complete life cycle analysis of pork production. Rather it provides a construction resource inventory that can later be combined with future analyses of operating different swine production facilities to generate a more systemic life cycle analysis of pork production.

Hoop barn-based swine facilities use less concrete, steel, lumber, thermoplastics, insulation, diesel fuel, and labor to construct than identically scaled conventional confinement facilities. More crushed rock and land is needed for hoop barn-based swine facilities but these are relatively small contributors to the total construction costs of swine facilities. The relative impacts of resource price changes are similar for both types and scales of swine facilities examined. The construction costs of hoop barn-based swine facilities are more sensitive to land prices than conventional confinement facilities, but land price is a relatively minor factor in total construction costs. Increasing the scale of facilities from 5,200 pigs to 15,600 pigs reduces construction costs per pig space regardless of system, but the magnitude of reduction is less for hoop barn-based facilities than conventional confinement facilities. Regardless of method for estimating construction cost, a swine production facility producing 5,200 market pigs annually and using hoop barns for gestation and grow-finish costs less to build per pig space than a conventional confinement swine facility producing either 5,200 or 15,600 market pigs annually. In terms of construction resource use and costs, hoop barns for swine are a lower cost alternative that is less scale dependant than conventional confinement facilities. As competition for construction resources increase the cost advantages of building hoop barn-based swine facilities is expected to increase.

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Table 1. Pork production systems compared.

	System	
Production phase	Conventional	Hoop barn-based
Breeding and Gestation barns	individual stalls with deep pit	group pens in bedded hoop
Farrowing[a]	crates with pull plug system	crates with pull plug system
Nursery	pens with shallow pit	pens with shallow pit
Grow-finish	pens with deep pit	pens in bedded hoop barns

[a] Manure from farrowing building stored in gestation pit (conventional) or adjacent outside storage pit (hoop barn-based).

Table 2. Pig flow parameters [a].

Weaned pigs per litter, pigs	9.2
Litters of weaned per mated female, litters/yr	2.3
Farrowing rate, litters born/sows mated	77.6%
Nursery mortality rate	2.9%
Grow-finish mortality rate	3.9%
Sow herd replacement rate	60.0%
Pig age at weaning, d	21.0
Maximum pig age at market, d	180.0

[a] Based on USDA (2007) and Pig CHAMP (2008).

Table 3. Pig spaces needed by production phase for 2 levels of annual pig production.

	5,200 pigs		15,600 pigs	
Production Phase	spaces	turns/yr	spaces	turns/yr
Breeding and gestation	310	na	900	na
Farrowing	48	13.0	140	13.0
Nursery	880	6.5	2,600	6.5
Grow-finish	1,600	3.3	4,800	3.3

Table 4. Summary of pig facilities examined.

Production level/phase	Building dimensions, m × m	Area/thermal resistance, MJ/hr-°C	Gross Area[a] m^2/pig	Net Area[b] m^2/pig	Description
5,200 pigs/yr					
Farrowing[c]	21.9 × 13.4	0.56	6.1	3.3	4 rooms of 12 crates, pull plug gutter to 2.4 m pit
Nursery	30.5 × 15.5	0.79	0.5	0.4	4 rooms of 22 pens, 1.2 m pit
Grow-Finish					
Conventional	92.0 × 15.5	6.38	0.9	0.8	4 rooms of 8 pens, 2.4 m pit
Hoop-based	21.9 × 9.1		1.0	1.0	8 hoop barns with 1 sort/load area, 1 pen/barn
Gestation					
Conventional	52.4 × 13.4	3.72	2.3	1.3	individual gestation stalls, 2.4 m pit
Hoop-based	21.9 × 9.1		5.8	5.2	9 hoop barns, 2 groups pens with 36 feed stalls/barn
Storage	18.3 × 18.3				bedding storage, 65% of area allocated to storage
15,600 pigs/yr					
Farrowing[c]	73.2 × 13.4	1.55	7.0	3.3	10 rooms of 14 crates, pull plug gutter to 2.4 m pit
Nursery	41.1 × 15.5	1.01	0.5	0.3	2 barns with 1.2 m pit, 4 rooms of 30 pens/barn
Grow-Finish					
Conventional	61.3 × 15.5	4.43	0.8	0.7	4 barns with 2.4 m pit, 1 room of 20 pens/barn
Hoop-based	21.9 × 9.1		1.0	1.0	24 hoop barns with 4 sort/load areas, 1 pen/barn
Gestation					
Conventional	70.7 × 13.4	4.78	2.1	1.3	2 barns with 2.4 m pit, individual gestation stalls
Hoop-based	21.9 × 9.1		5.5	5.0	25 hoop barns, 2 groups pens with 36 feed stalls/barn
Storage	18.3 × 18.3				bedding storage, 2 entire hoop barns

[a] Total area under cover.
[b] Total area under cover minus walkways and alleys.
[c] Manure storage for the farrowing facility in the conventional confinement system is the 2.4 m deep pit under the gestation facility. Manure storage for the farrowing facility in the hoop barn-based system is a separate 2.4 m deep pit adjacent to the farrowing facility.

Table 5. Density and estimated value of construction materials examined.

Material	Density g/cm^3	Est.Value $/kg	Examples and Uses
Concrete[a]	2.40	$0.04	building foundations, walls, manure storage, slats
Steel[b]	8.08	$1.14	concrete reinforcing bar, siding, gating, hoop trusses
Lumber[c]	0.53	$0.23	building frame, trusses
Thermoplastics[d,e]	0.95	$1.00	flooring, pens, building curtains, hoop barn tarps
Insulation[f,g]	0.03	$0.59	ceiling and walls of non-hoop buildings
Crushed rock[h]	2.75	$0.02	access roads

[a] Koenig and Runestad (2005).
[b] BSCI (2008).
[c] Rao (2008).
[d] High density polyethylene.
[e] BT (2008).
[f] Loose fill cellulose.
[g] USDOE (2005).
[h] Hammond and Jones (2008).

Table 6. Construction resource use for swine production facilities.

		Conventional		Hoop barn-based	
	Pigs sold annually	5,200	15,600	5,200	15,600
Farrowing[a]	Concrete, kg	150,464	451,393	287,534	691,769
	Steel, kg	20,508	32,092	22,499	38,404
	Lumber, kg	6,651	19,561	6,651	19,561
	Thermoplastics, kg	16,053	30,172	12,466	26,585
	Insulation, kg	2,433	6,415	2,433	6,415
	Diesel fuel, l	0	0	38	124
Nursery	Concrete, kg	288,653	782,598	288,653	782,598
	Steel, kg	27,093	64,662	27,093	64,662
	Lumber, kg	12,468	26,238	12,468	26,238
	Thermoplastics, kg	12,159	30,892	12,159	30,892
	Insulation, kg	3,192	5,110	3,192	5,110
	Diesel fuel, l	46	466	46	466
Grow-Finish	Concrete, kg	1,237,294	3,435,800	678,191	2,074,200
	Steel, kg	28,740	113,264	11,024	33,336
	Lumber, kg	33,569	89,960	18,560	56,136
	Thermoplastics, kg	3,084	4,792	1,074	3,216
	Insulation, kg	6,759	17,576	0	0
	Diesel fuel, l	802	2,146	0	0
Gestation	Concrete, kg	696,669	1,709,790	606,078	1,683,550
	Steel, kg	38,329	107,144	27,333	75,925
	Lumber, kg	13,115	34,920	16,812	46,700
	Thermoplastics, kg	711	1,610	1,350	3,750
	Insulation, kg	3,402	9,116	0	0
	Diesel fuel, l	281	468	0	0
Bedding storage	Concrete, kg	0	0	56,296	173,218
	Steel, kg	0	0	2,137	9,574
	Lumber, kg	0	0	268	826
	Thermoplastics, kg	0	0	124	380
Access Roads	Crushed rock, kg	132,000	264,000	303,600	475,200
	Diesel fuel, l	34	64	78	121
Site Preparation	Diesel fuel, l	399	830	591	1,110
Total for all production facilities					
	Concrete, kg	2,373,080	6,379,581	1,916,752	5,405,335
	Steel, kg	114,670	317,162	90,086	221,901
	Lumber, kg	56,029	151,074	44,985	129,856
	Thermoplastics, kg	32,007	67,466	37,123	64,823
	Insulation, kg	19,361	51,017	9,210	24,325
	Crushed rock, kg	132,000	264,000	303,600	475,200
	Diesel fuel, l	1,562	3,910	753	1,700
	Land, m^2	11,868	24,870	16,671	32,117
	Labor, hr	23,000	45,900	14,300	39,300

[a] Manure storage for the farrowing facility in the conventional confinement system is the 2.4 m deep pit under the gestation facility. Manure storage for the farrowing facility in the hoop barn-based system is a separate 2.4 m deep pit adjacent to the farrowing facility.

Table 7. Estimated construction costs for swine production facilities.[a]

		Conventional		Hoop barn-based	
	Pigs sold annually	5,200	15,600	5,200	15,600
Farrowing[b]	Materials	$87,008	$180,488	$92,593	$211,211
	Labor	$36,789	$92,372	$50,042	$133,950
	Total/farrowing crate	$2579	$1,949	$2,972	$2,465
Nursery	Materials	$86,678	$233,986	$86,678	$233,986
	Labor	$42,913	$107,006	$42,913	$107,006
	Total/pig space	$147	$131	$147	$131
Grow-Finish	Materials	$310,033	$764,378	$99,996	$307,094
	Labor	$192,205	$250,348	$36,690	$111,928
	Total/pig space	$314	$211	$85	$87
Gestation	Materials	$264,429	$418,357	$104,823	$291,179
	Labor	$230,703	$251,018	$49,131	$136,475
	Total/sow space	$1,597	$744	$497	$475
Storage	Materials	0	0	$12,725	$25,832
	Labor	0	0	$4,898	$9,796
	Total/m^2	0	0	$53	$53
Site Preparation	Land	$23,200	$48,800	$32,800	$63,200
	Materials	$10,980	$21,053	$25,283	$39,537
	Labor	$723	$1,505	$1,071	$2,013
	Equipment	$2,222	$4,623	$3,289	$6,181
	Total/m^2	$3.13	$3.06	$3.75	$3.45
Subtotal Material and Land		$782,328	$1,667,062	$454,898	$1,172,039
Subtotal Labor and Equipment		$505,555	$706,872	$188,034	$507,349
Total		$1,287,883	$2,373,934	$642,932	$1,679,388
Construction cost per market pig sold		$248	$152	$124	$108

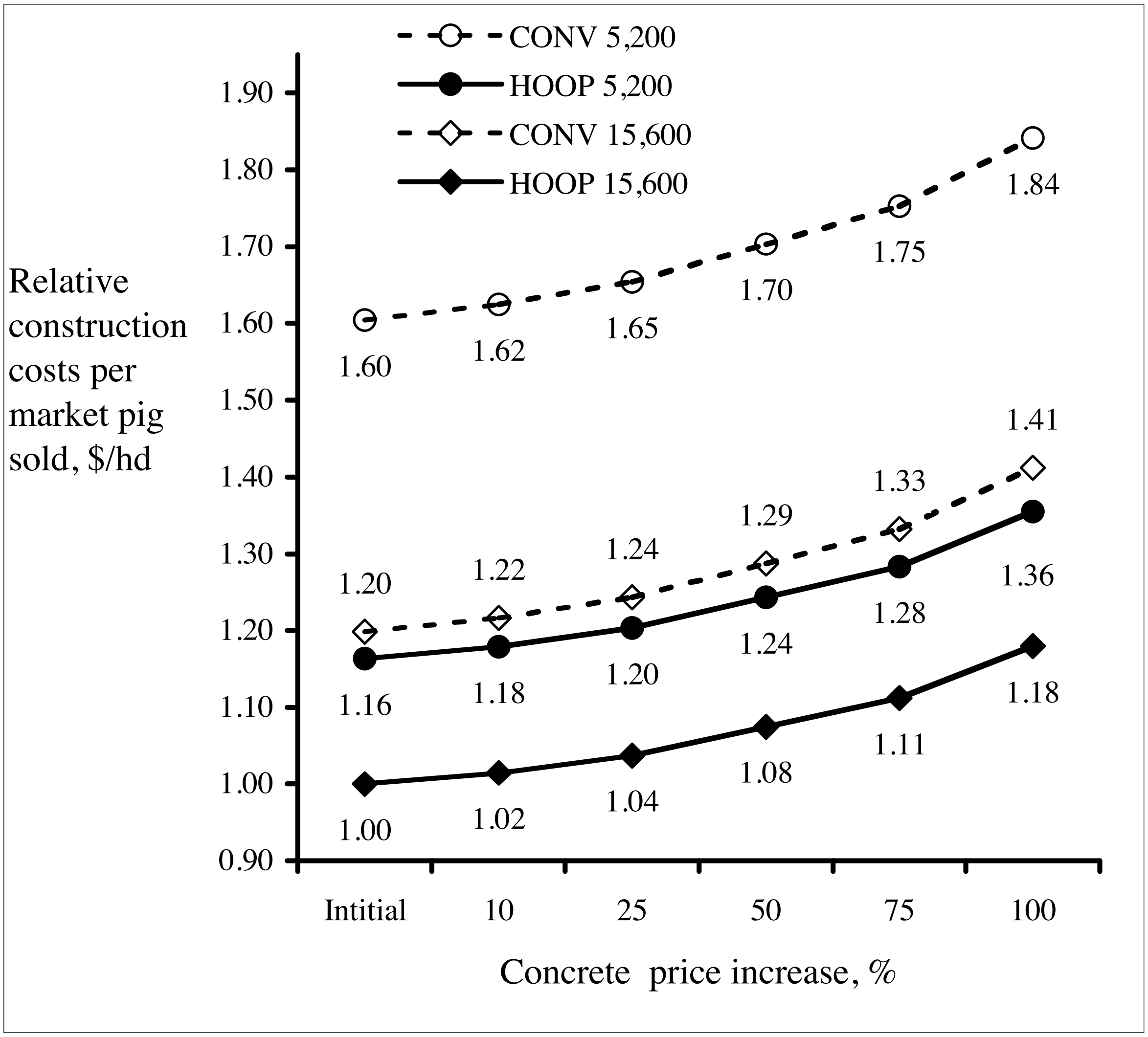
[a] Mossman and Plotner (2006).
[b] Manure storage for the farrowing facility in the conventional confinement system is the 2.4 m deep pit under the gestation facility. Manure storage for the farrowing facility in the hoop barn-based system is a separate 2.4 m deep pit adjacent to the farrowing facility.

Table 8. Estimated construction costs for swine facility complexes based on material mass[a].

	Conventional		Hoop barn-based	
Pigs sold annually	5,200	15,600	5,200	15,600
Concrete	$94,932	$255,183	$76,670	$216,213
Steel	$130,724	$361,565	$102,698	$252,967
Lumber	$12,887	$34,747	$10,346	$29,867
Thermoplastics	$32,007	$67,466	$37,123	$64,823
Insulation	$11,423	$30,100	$5,434	$14,352
Crushed Rock	$2,640	$5,280	$6,072	$9,504
Fuel	$1,562	$3,910	$753	$1,700
Land	$23,200	$48,800	$32,800	$63,200
Labor[b]	$460,000	$918,000	$286,000	$786,000
Total	$769,375	$1,725,051	$557,896	$1,438,626
Construction cost per market pig sold	$148	$111	$107	$92

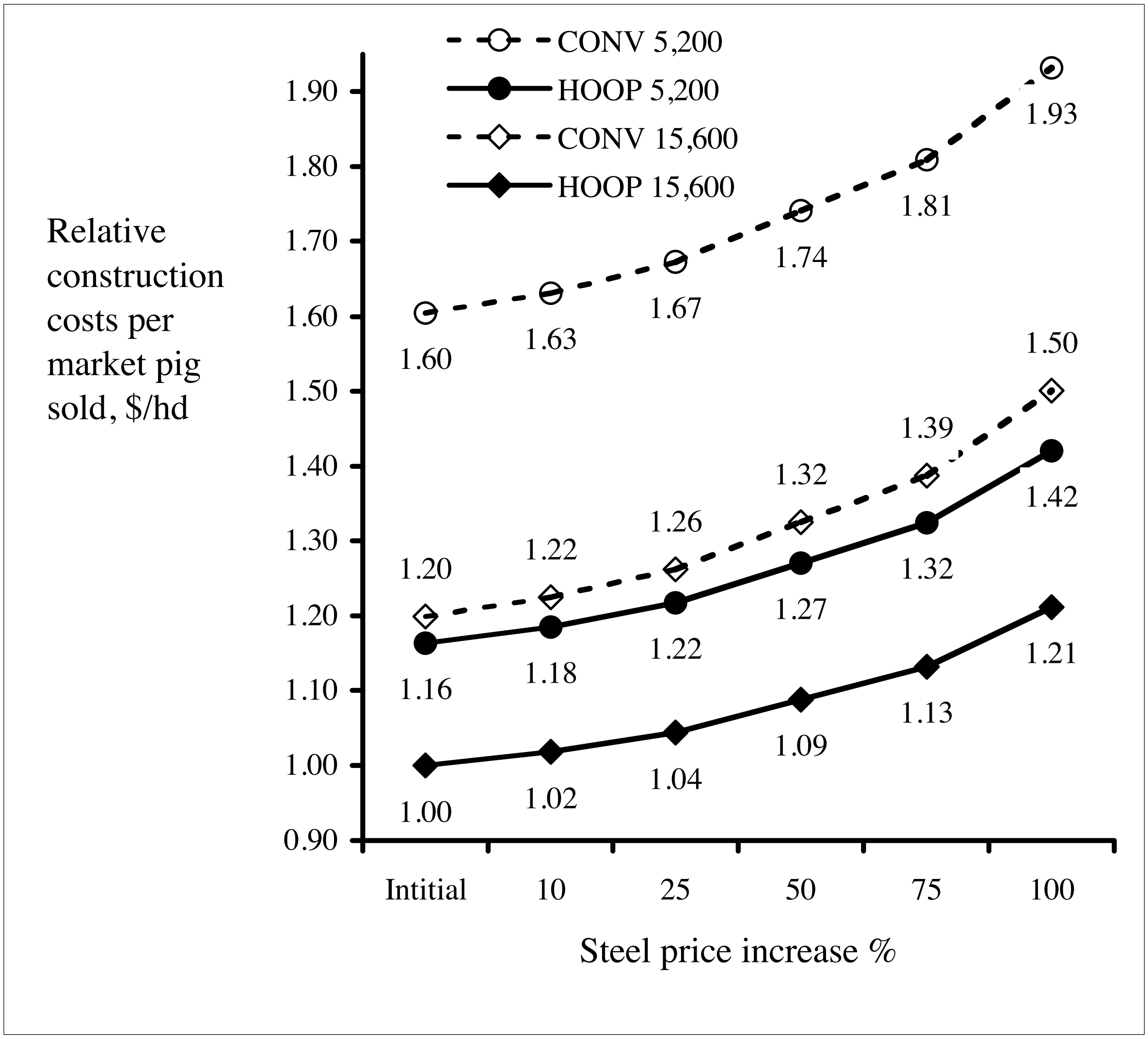
[a] Calculated by multiply material masses reported in table 6 by estimated market values of materials presented in table 5.
[b] Calculated by multiplying hours of labor reported in table 6 by $20/hr.

Figure 1. Construction cost sensitivity to change in concrete prices for different types and scales of pig production facilities[a].



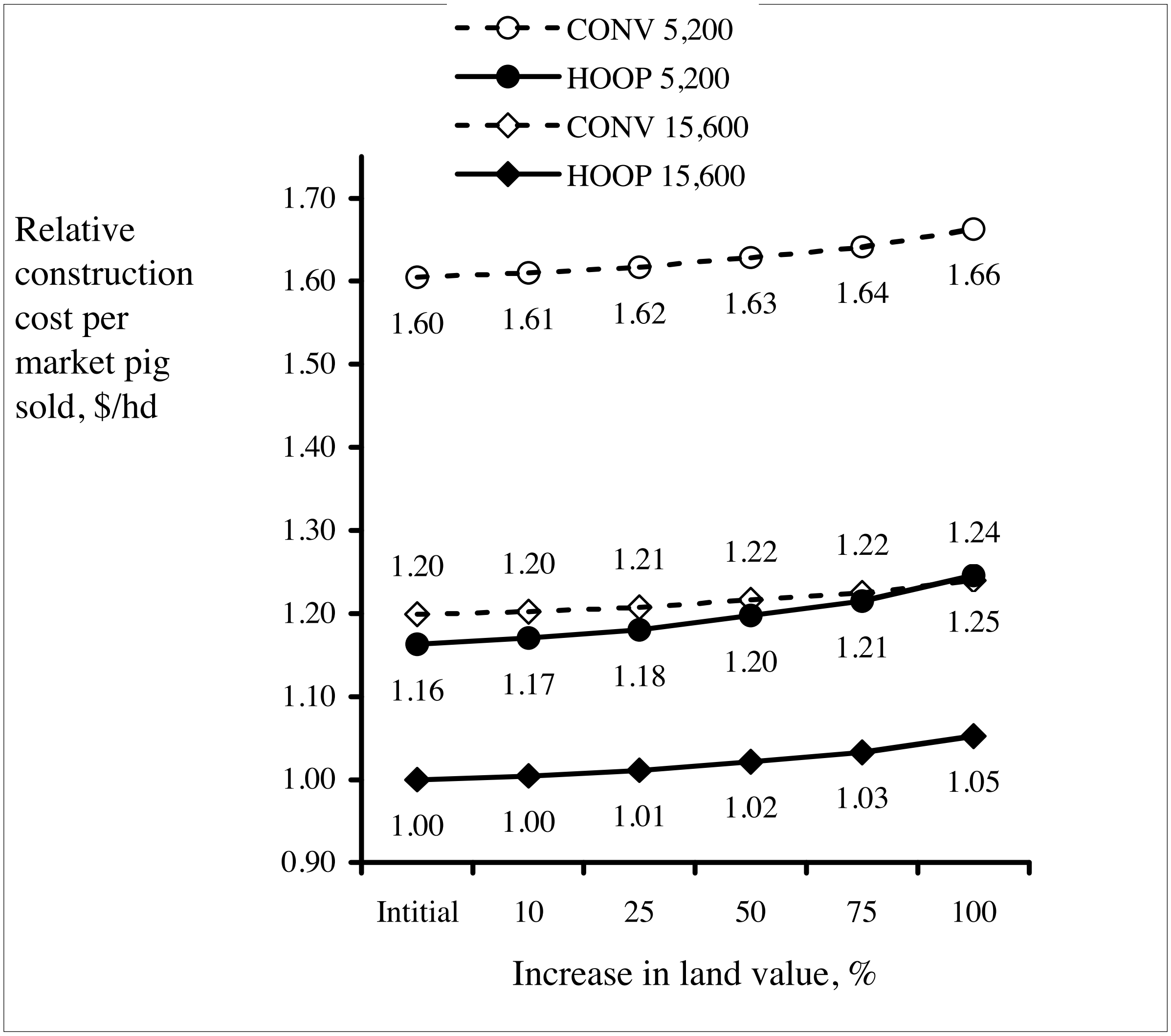
[a] HOOP or CONV and 15,600 or 5,200 represent hoop barn-based pig production or conventional confinement facilities scaled to produce 15,600 or 5,200 market pigs annually.

Figure 2. Construction cost sensitivity to change in steel prices for different types and scales of pig production facilities[a].



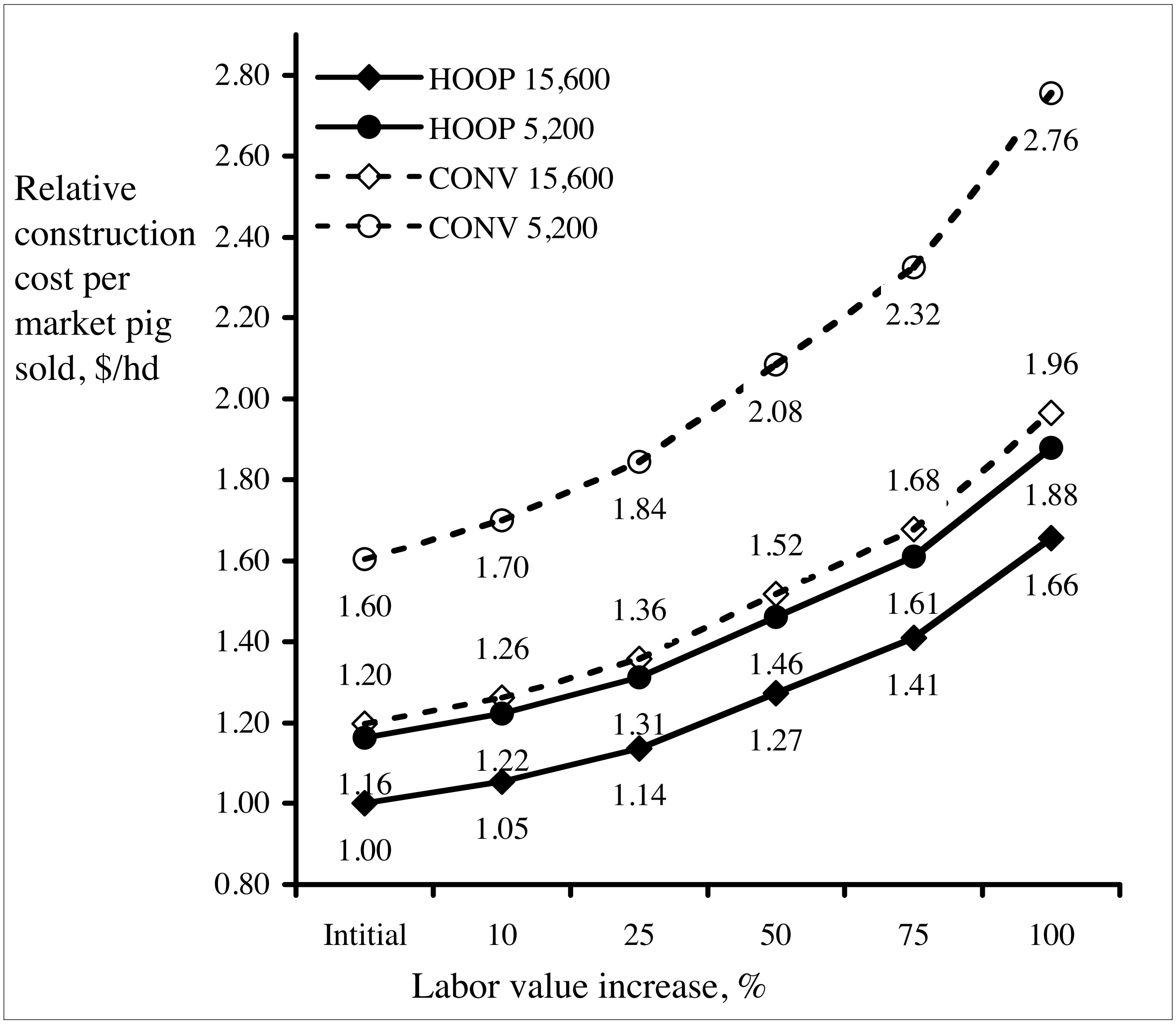
[a] HOOP or CONV and 15,600 or 5,200 represent hoop barn-based pig production or conventional confinement facilities scaled to produce 15,600 or 5,200 market pigs annually.

Figure 3. Construction cost sensitivity to change in land values for different types and scales of pig production facilities[a].



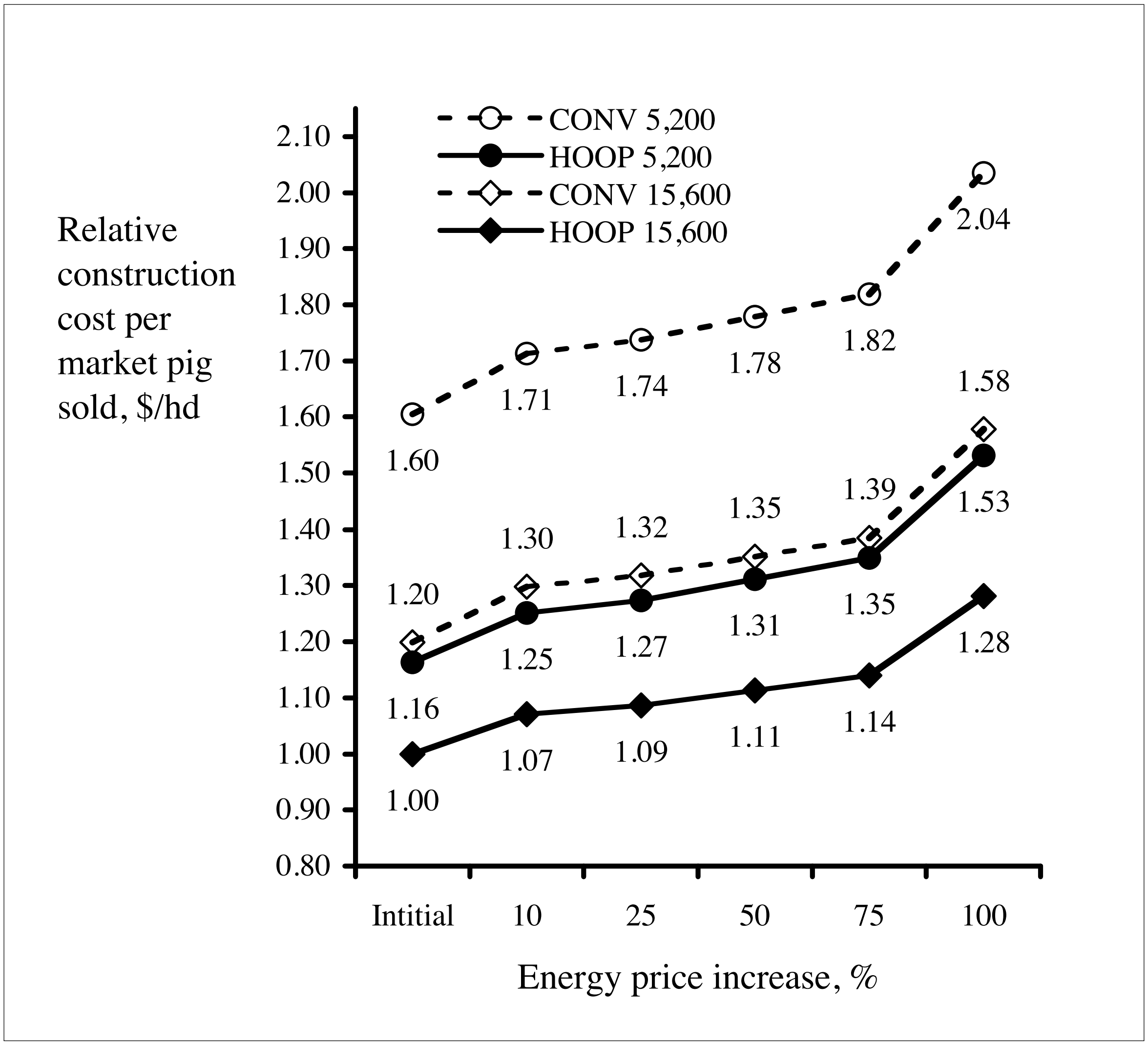
[a] HOOP or CONV and 15,600 or 5,200 represent hoop barn-based pig production or conventional confinement facilities scaled to produce 15,600 or 5,200 market pigs annually.

Figure 4. Construction cost sensitivity to change in construction labor prices for different types and scales of pig production facilities[a].



[a] HOOP or CONV and 15,600 or 5,200 represent hoop barn-based pig production or conventional confinement facilities scaled to produce 15,600 or 5,200 market pigs annually.

Figure 5. Construction cost sensitivity to change in energy prices for different types and scales of pig production facilities[a].



[a] HOOP or CONV and 15,600 or 5,200 represent hoop barn-based pig production or conventional confinement facilities scaled to produce 15,600 or 5,200 market pigs annually.

CHAPTER 4: ENERGY AND CARBON INVENTORY OF IOWA SWINE PRODUCTION FACILITIES

A paper to be submitted to *Agricultural Systems*

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ABSTRACT

Energy and carbon use by different types and scales of pig production systems are assumed to be different, but have not been critically examined. This study evaluates energy and carbon use by two types of facilities—conventional confinement and hoop barn-based—within farrow-to-finish pig production systems scaled to produce 5,200 and 15,600 market pigs annually in Iowa. Conventional confinement facilities are typical of pork industry practice in the United States and are characterized by individual gestation stalls and 1,200 head grow-finish buildings with slatted concrete floors and liquid manure systems. The hoop barn-based alternative uses group pens in bedded hoop barns for gestation and finishing. Both systems use climate controlled farrowing facilities with individual farrowing crates as well as climate controlled nursery facilities. Resources such as energy and carbon can be categorized as embodied or operating based on how they are used. Embodied energy refers to the quantity of energy required to manufacture, provide, or supply a product, material, or service.

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Embodied carbon is the CO_2 and other greenhouse gases released during production of a material or service. Operating energy is the energy required for a system to function on a daily basis. Energy consumption is commonly used to estimate greenhouse gas emissions. Operating carbon refers to the amount of greenhouse gases released by consumption of operating energy expressed in CO_2 equivalents. Pig facility type affects embodied and operating energy and carbon associated with pig production and may markedly impact life cycle assessment of pork. This analysis indicates that hoop barn-based pig production may more effectively use limited non-solar energy resources for pig production than conventional confinement facilities.

Keywords: Swine production, hoop barns, embodied energy, operating energy

1. Introduction

Meat production and demand is increasing throughout the world, and pork is the most widely consumed meat globally (Delgado et al., 1999; FAO, 2006). The United States is the world's second largest producer of pork (den Hartog, 2005) and has long been a leader in modern pork production. United States pig production is centered in Iowa (USDA, 2002b) and is a major influence on the economic and ecological condition of that region. Historically the availability and market price of fossil fuels has minimized pressure to critically consider all uses of energy in pig production. Rising energy prices, global conflicts, and recognition of the environmental impacts of using fossil fuels are increasing awareness and incentive to optimize use of these limited resources.

Energy use can be classified into 2 broad categories— embodied and operating. Embodied energy refers to the quantity of energy required to manufacture, provide, or supply a product, material, or service (Hammond and Jones, 2008). In pig production, energy used to produce facility components such as concrete, steel, plastics, and lumber are examples of embodied energy. Operating energy is the energy required for a system to function on a daily basis. The energy value of the feed directly consumed by pigs as well as liquid fuels and electricity used to modify the pig environment are examples of operating energy for pig production.

Pig feed, bedding materials, liquid fuels, and electricity have an embodied energy value, but that value is highly dependent upon production assumptions that are beyond the scope of this paper. In our assessment an input is either an operating or an embodied energy component. If an input is used to provide the structural framework for pig production—concrete, metal, plastics—it is classified as an embodied energy component and the energy associated with manufacture of that component is included. If an input is consumed during the daily operation of a pig facility—feed, liquid fuels, electricity—it is classified as an operating energy component and only the energy released by the consumption of the input—the operating energy—is included. The embodied energy associated with production of operating energy components are not included in this analysis.

Embodied carbon is the CO_2 and other greenhouse gases released during the production of a product (Hammond and Jones, 2008) and represents the initial global climate altering emissions associated with a product. Emissions of compounds associated with global climate change occur during fuel consumption and are often expressed in terms of CO_2 equivalents. The operating carbon of a pig production facility is simply the CO_2 equivalents released through consumption of operating energy inputs associated with pig production. Operating energy components have an embodied carbon associated with their provision, but this is not included in this analysis. In this paper, embodied carbon is exclusively affiliated with embodied energy inputs and operating carbon is exclusively associated with consumption of operating energy components.

Accurate life cycle assessment relies on current and comprehensive information relating to all aspects of a particular process. Comprehensive analysis regarding embodied energy and carbon of different pig facilities as well as the operating energy and resulting global climate altering emissions, or CO_2 equivalents, associated with producing pigs in those facilities has not been reported. To date, life cycle assessments for modern pig production have focused on the grow-finish phase of production and particularly the embodied energy of feedstuffs (Ericksson et al., 2005; Meul et al., 2007). Although these analyses address a major portion of the total energy used for pig production, they do not account for all energy use. The objective of this project is to estimate the embodied energy and carbon of different types and scales of Iowa swine production facilities. The operating energy and corresponding CO_2 equivalent emissions from raising pigs in different types and scales of pig production facilities are also estimated.

2. Methods

This project considers energy inputs (embodied and operating) into a pig facility based on physical material flows. Energy used to produce facility components such as steel, plastics, and lumber are examples of embodied energy. Operating energy inputs are used directly for pig production and include feed consumed by the pigs, liquid fuels used to heat buildings and remove manure, and electricity used to ventilate and illuminate buildings. To borrow terminology from economics, operating energy can be considered analogous to variable costs— costs that are incurred (energy that is used) only if actual pig production occurs. Alternatively, embodied energy can be viewed as fixed costs— costs that are incurred (energy that is used) to create and maintain the means of production even if no pigs are produced.

Energy inputs are then used to calculate embodied carbon and emission of CO_2 equivalents. Embodied carbon is the CO_2 and other greenhouse gases released during the production of facility components (Hammond and Jones, 2008) and represent the initial CO_2 cost of building different types and scales of pig facilities. Emissions released by consumption of operating energy represent the annual addition of CO_2 equivalents resulting from raising pigs using a particular housing system.

Two types of facilities— conventional confinement and bedded hoop barn-based— are considered within identically scaled farrow-to-finish production systems. The conventional confinement system is typical of pork industry practice in the United States and is characterized by individual gestation stalls and 1,200 head grow-finish buildings with slatted concrete floors and liquid manure systems. The hoop barn-based alternative uses group pens in bedded hoop barns for gestation and finishing. Both systems have been previously described by the authors (Lammers et al., 2009) and will use climate controlled farrowing facilities with individual farrowing crates as well as climate controlled nursery facilities. Energy and carbon use is also related to volume of pig flow and so pig production systems sized to produce batches of either 400 or 1,200 market pigs every 28 d, or 5,200 and 15,600 market pigs annually are compared.

2.1. Embodied energy and carbon of swine production facilities

Five primary building materials are examined: concrete, steel, lumber, insulation, and thermoplastics. The mass of building materials reported by Lammers et al. (2009) for each type of pig production facility was multiplied by embodied energy and carbon data presented by Hammond and Jones (2008). Globally standardized embodied energy and carbon values for building materials have not been recognized. The use of one open-access database for all embodied energy and carbon values (Hammond and Jones, 2008) insures that materials are compared on an equal basis as well as allowing for peer review and future analysis. The actual values of embodied energy and carbon present in a given mass of building materials used in pig production facilities may be different from the results of this analysis. However, the relative difference in embodied energy and carbon between the different types and scales of pig production facilities are expected to remain stable. Table 1 summarizes material density, embodied energy, and embodied carbon assumptions for the building materials examined.

Another source of embodied energy and carbon of pig buildings is the diesel fuel used for earthwork associated with the construction of pig facilities. Estimated diesel fuel use for these activities have been reported by Lammers et al. (2009). The volume of diesel fuel reported by Lammers et al. (2009) was multiplied by an energy value of 38.46 MJ/L (Downs and Hansen, 2007) to estimate the energy used for earthwork. The energy from earthwork activities associated with construction of pig facilities is included in the estimate of embodied energy of pig facilities. For every GJ of diesel fuel combusted an estimated emission of 82.73 kg CO_2 equivalents occurs (IPCC, 2006). Embodied carbon from diesel fuel used for earthwork was calculated by multiplying the energy in GJ from diesel fuel associated with construction by 82.73 kg CO_2 equivalents.

Embodied energy and carbon of pig production facilities represent one-time inputs that occur at the time of construction. To take into account potentially different useful lifespans of different pig facilities it is appropriate to divide total embodied energy and carbon from construction by the estimated useful lifespan of a facility. Construction costs of conventional confinement facilities are often assumed to be paid over 15 or 20-year useful lifespans. Hoop barns are often used for similar time frames, although replacement of the tarp is sometimes necessary after 10 or 12 years of use. Two different scenarios are considered for hoop barns. The first assumes that the useful lifespan of hoop barns are identical to the useful lifespan of conventional confinement facilities. The second includes additional embodied energy and carbon required to replace all tarps on hoop barns once during a 15 or 20-year useful lifespan.

2.2 Operating energy of pig production facilities

Energy use for one 365-d period was modeled for each phase of pig production. This analysis examines energy use of a production facility and includes thermal environment control (heating and ventilation), pumping water, cleaning the facility between groups of pigs, lighting, consumed pig feed, bedding use, and removing manure slurry or bedding pack from the building. Assessments of operating energy are highly dependent on where the system boundary is drawn. For this analysis the boundary is the pig production facility, more explicitly the actual pig barn. Activities that occur within the pig barn are included; activities that occur outside of the actual barn are not. For example energy used to produce the feed, transport manure slurry or bedding pack to fields, and other related activities are not addressed in this paper. This boundary separates quantification of energy use associated with a particular type of building from energy use associated with generalized pig production.

Initial start-up energy for a new building can be significant, for example bringing a newly constructed nursery building or one that has been idle for an extended period of time up to an acceptable temperature in the middle of winter requires a large input of energy simply to warm the building structure. For our analysis, production is assumed to have reached steady-state; i.e. the buildings are in operation and pigs are regularly flowing through them. Two performance scenarios are considered. The first analysis assumes that feed conversion and sow reproductive performance is equal for conventional confinement and the hoop barn-based alternative. The second analysis incorporates reported performance differences for pigs and sows housed in hoop barns.

2.2.1 Thermal Climate Control

Thermal climate is the sum effects of air temperature, moisture, and airflow experienced by pigs (Curtis, 1983). Building characteristics and exterior temperatures as well as the number and size of pigs present affect the thermal climate of a pig barn. Mechanically ventilated pig barns commonly use LP gas and electricity to provide a suitable thermal environment for pigs. Hoop barns are naturally ventilated buildings that rely on bedding and pig behavior to modify thermal environment. This section addresses energy use for mechanical control of thermal climate in pig barns. Bedding is discussed in a following section.

Other than initial site selection, producers have little control over exterior temperatures. Historic temperature data is available for several locations in Iowa (Kjelgaard, 2001; ISU, 2008). Hourly temperature readings for a typical meteorological year for the 1961–1990 time period have been summarized by location into reference tables commonly referred to as BIN data (Kjelgaard, 2001). BIN data consists of a series of 5°F dry bulb temperature ranges or bins, where every hour in a typical meteorological year that falls within a range is included in the appropriate bin (Kjelgaard, 2001). This allows modeling of energy used for heating and cooling based upon temperatures differences and time.

In Iowa, latitude is more predictive of thermal environment than longitude. Mason City, Iowa, 43.1°N, 93.2°W shares a latitude that is similar to 6 of the top 10 pig producing counties in Iowa (USDA, 2002a). Energy used for thermal environment control at Mason City, Iowa was modeled using annual BIN data as exterior temperature for one complete year— 365 d or 8,760 h. Assumptions relating to building dimensions, thermal resistance and pig stocking density are summarized in table 2.

Farrowing, nursery, and finishing barns are emptied and cleaned between groups of pigs. This results in those buildings housing zero pigs for 1-15% of the year. When there are no pigs in a building, no heat production from pigs occurs, ventilation rates can be dramatically reduced, and acceptable temperature range is usually allowed to expand. Our model assumes that sows enter the farrowing facility 3 days prior to farrowing and litters are weaned at 21 d of age. Our model assumes 13 turns of the farrowing facility in 1 year, thus the building is occupied by pigs for 85% of the year (equation 1).

$$\textit{Equation 1. Occupancy of farrowing building}$$
$$\frac{24\ d/group\ of\ sows \times 13\ turns/yr}{365\ d/yr} = 85\%\ of\ year$$

Our model assumes pigs are weaned at 21 d of age and enter the nursery weighing 5.4 kg. Fifty days later the pigs weigh 32.2 kg and enter the grow-finish building. There are 6.5 groups of pigs that move through a nursery in 1 yr, thus the nursery is occupied by pigs for 89% of the year (equation 2).

$$\textit{Equation 2. Occupancy of nursery building}$$
$$\frac{50\ d/group\ of\ pigs \times 6.5\ turns/yr}{365\ d/yr} = 89\%\ of\ year$$

Our model assumes pigs enter the grow-finish building at 71 d of age weighing 32.2 kg and are marketed 109 d later at 138.3 kg. There are 3.3 groups of pigs that move through a grow-finish building in 1 yr, thus the grow-finish building is occupied by pigs for 99% of the year (equation 3).

$$\mathit{Equation\ 3.\ Occupancy\ of\ grow-finish\ building}$$
$$\frac{109\ d/group\ of\ pigs \times 3.3\ turns/yr}{365\ d/yr} = 99\%\ of\ year$$

Our model assumes that the average pig in the nursery and grow-finish building weighs 18.8 and 85.3 kg respectively. Table 3 summarizes modeled building occupancy, pig weight, heat production, target temperature, and minimum ventilation rate for each production phase. When no pigs are in a given building it is assumed that heat production is zero, that ventilation is reduced to 650 L $\times$ min^{-1} $\times$ building^{-1}, and that room temperature is maintained between 10–32.2°C.

Worksheets from MidWest Plan Service publications (MWPS, 1987, 1990a, b) were combined with historic temperature data for Mason City, Iowa (Kjelgaard, 2001), and model assumptions presented in tables 2 and 3 to estimate energy used for thermal climate control of pig facilities. The step-by-step process for calculating energy use for thermal control of grow-finish facilities within a system producing 15,600 market pigs annually has been presented previously (Lammers, 2009). Calculations for the grow-finish facilities within the 5,200 market pig system and for the farrowing, nursery, and gestation facilities in both systems followed a similar process with appropriate adjustments made for differences in pig size and building characteristics.

Ventilation of pig buildings is necessary to provide proper environment for the pigs and stockmen. Ventilation systems remove heat from a building and heat loss through ventilation was calculated using equations from MWPS publications (MWPS, 1987, 1990a, b). Cold weather ventilation rates for different sized pigs are presented in MWPS publications (MWPS, 1990a, b). These ventilation rates are the minimum rates to maintain acceptable air quality and humidity (MWPS, 1990a, b). Hourly heat loss from ventilation was calculated using hourly temperature differences and pig size specific ventilation rates. Our analysis assumes that building heaters are ventilated to the outdoors and do not require additional room ventilation.

Although heat is lost from the building through surfaces and the ventilation system, heat is added to the building by the pigs themselves. Sensible heat production by pigs of different body weights and at different room temperatures are presented in table 3. To calculate heat production by pigs in a given hour, sensible heat production from one pig was multiplied by the number of pigs in a particular building

The difference between heat produced by pigs and the sum of heat loss from building surfaces and the minimum ventilation were calculated for 8,760 h (1 year) of production for each location. If the hourly difference was negative, additional heat inputs were necessary and if the difference was positive additional cooling tactics may be required. Hourly heat input needs were summed to determine annual heat input requirements. Based on manufacturer literature and conversations with heating equipment representatives it was assumed that heating strategies would be 98% efficient. Thus annual heat input requirements were divided by 98% to estimate total energy used for heating during a typical year.

Most mechanically ventilated pig buildings are equipped with multiple, variable-speed fans that are governed by thermostats. In mechanically ventilated pig buildings, air exchange to maintain interior air quality and remove humidity from the building occurs at a constant, minimal rate regardless of exterior weather conditions. The cold weather ventilation rate is the minimal rate necessary to maintain acceptable air quality and humidity and is based on pig body weight (MWPS, 1990a, b). As exterior temperatures increase, the interior temperature of pig facilities also increases. As interior temperatures increase, ventilation rates also increase for most pig facilities. A common approach to ventilating pig barns is to designate one set of fans for maintaining air quality with another larger capacity system used for temperature modification.

For each type of pig facility, 2 sets of commercially available fans with adequate capacity for a particular task—air quality or temperature modification— were selected from a third party database (BESS, 2008). Hours of operation for each set of fans were estimated for each location by combining annual BIN data with pig and building characteristics. Energy use for air exchange was then calculated by multiplying the hours of operation for each fan system by reported fan efficiencies (BESS, 2008). To standardize comparisons, fan system efficiencies of 339.8 L $\times$ min^{-1}/W and 736.2 L $\times$ min^{-1}/W (12 cfm/W and 26 cfm/W) were assumed for air quality and temperature modification systems respectively.

The environment of the farrowing facility is a unique situation because the thermal needs of both the newborn pig and the adult sow must be addressed. Although the newborn pig has no practical upper limit for room temperature, the sow will reduce feed intake and subsequent milk production if she becomes uncomfortably warm. To address these different requirements, the room temperature of the farrowing facility is assumed to be kept at 18.3°C with an allowable maximum of 21.1°C. The higher temperatures necessary for young pig comfort are achieved through the use of supplemental radiant heating that does not significantly contribute to overall room temperature. For each litter of pigs farrowed it was assumed that two 175 W heat lamps are used for 48 hours followed by 12 d of one 175 W heat lamp use.

2.2.2 Water

Water is essential to pig survival and growth and large quantities of water are used to clean most pig facilities. Wash water is usually heated and pressurized to assist in the cleaning process. Pumping water from a well to a pig facility as well as heating and pressurizing wash water requires energy and is included in our analysis. Water use assumptions used to calculate required water volume are included as Table 4. Appropriately sized well pumps were selected for the different facility sites based on water volume using MWPS guidelines (MWPS, 1987). For our analysis we assume a 0.37 kW (1/2 hp) motor with a pumping capacity of 20.8 L/min (330 g/h) at 275.8 kPa (40 psi). The National Association of Electrical Manufacturers (NEMA) is a trade association representing over 450 members and publishes technical standards and efficiency ratings for electrical motors (NEMA, 2009a). For our analysis we assume all electrical motors used are rated as NEMA Premium motors for efficiency. For pumping water, the 0.37kW electrical motor is assumed to have a 82.5% nominal efficiency (NEMA, 2009b). Volume of water, well pump capacity, and motor efficiency were used to calculate the amount of energy needed for pumping water from the well and pressurizing water lines used for drinking water.

Most conventional confinement facilities in Iowa are cleaned using portable pressure washers and a variety of designs and specifications are commercially available. For our analysis we assume that the pressure washer will deliver 20.8 L/min at 31 MPa. The washer will be powered by a 14.9 kW electric motor. This motor is assumed to have a nominal efficiency of 91.7% (NEMA, 2009b). The hours of motor operation needed for a particular task was calculated based on water usage and flow rates. Energy used for water delivery and pressurization was calculated by combining motor size, hours of operation, and nominal efficiency. The pressure washer will also be equipped with a diesel burner with capacity to raise the temperature of wash water by 60°C at 95% efficiency. The temperature of ground water in Iowa is approximately 8°C (USGS, 2008). It is assumed that wash water would be heated to 60°C. Heat energy necessary to increase the temperature of the wash water by 52°C was first calculated using the density and specific heat of water in combination with volume of wash water used. Energy used for heating wash water was then taken as 105% of the calculated heat energy.

2.2.3 Illumination

Illuminating pig facilities with electric lights is common in mechanically ventilated facilities. Adequate illumination is essential for conscientious stockmanship. ASAE (2005) characterizes different light sources and provides recommendations for light levels and photoperiods of pig facilities. Compact fluorescent lights with an efficiency of 68 lm/W were used in this analysis. Energy use for illumination in conventional confinement facilities was calculated using ASAE recommendations for pig facilities (ASAE, 2005). It was assumed that 100% of the floor area in the confinement facility would be illuminated and that hours of operation would match ASAE recommendations (ASAE, 2005) Hoop barns use some electric lights, but typically only 33–50% of the barn is illuminated. Natural lighting also allows reduction in the hours electrical lights are needed. Energy used for illuminating 50% of the total floor area was calculated for hoop barns. It was also assumed that hours of illumination in hoop barns would be 50% of ASAE recommendations because of natural lighting (ASAE, 2005).

2.2.4 Feed

Feed is typically the largest expense in a farrow-to-finish pig operation and the amount of energy associated with feed is also very large. The energy required to produce the raw ingredients for pig feed, process those components into a particular diet, and deliver the diet from the feed mill to a particular barn is not included in this report. This analysis considers only the energy used to move feed from on-site storage to feeders and the gross energy (GE) of the feed presented to the pigs. Energy use related to feed is closely linked to the amount of feed consumed and the energy density of the diet. Feed intake and growth efficiency assumptions for pigs housed in mechanically ventilated confinement facilities are presented in table 5.

A total of seven corn-soybean meal diets were considered for modeling purposes. Two reference diets were used for adult animals—one for gestating sows and one for lactating sows (Holden et al., 1996). The five corn-soybean meal control diets fed to growing pigs in an earlier study were used as the reference diets for growing pigs in this analysis (Lammers et al., 2008b). All diets were formulated to meet or exceed NRC recommendations for metabolizable energy, lysine, methionine, threonine, tryptophan, and available phosphorus for a specific category of pigs (NRC, 1998). Diet formulations were combined with GE values of ingredients from literature (Sauvant et al., 2004) to calculate the GE of mixed diets fed to pigs. The GE and amount of each diet fed was used to calculate the GE value of an average kg of pig feed in the production model. On average, the GE value of pig feed fed from farrow-to-finish was 16.0 MJ/kg. Total feed energy was calculated by multiplying feed use per market pig sold by GE value of the feed by the total number of market pigs sold in a particular system.

The pig production model presented by Lammers et al. (2009) results in each sow producing the equivalent of 19.7 market pigs annually. Taking into consideration nursery and grow-finish mortality rates of 2.9% and 3.9%, respectively, the equivalent of 51.0 kg of nursery feed and 307.5 kg of grow-finish feed is directly attributable to each pig sold in the conventional confinement system. An additional 15.6 kg of lactation feed and 37.0 kg of gestation feed are also allocated to each market pig sold in the conventional confinement system. Thus each pig sold was attributed 411.1 kg of feed for the conventional system. Under the initial assumption of equal feed consumption, each pig sold from the hoop barn-system was also attributed 411.1 kg of feed.

Commercially available feed augers were selected to move feed from bulk storage bins to pig feeders. The size of electric motors used for feed delivery in a particular facility was determined based on auger and feed characteristics (APS, 2008). All electrical motors used for feed delivery were assumed to have a nominal efficiency of 82.5% (NEMA, 2009b). Hours of operation for feed auger motors were calculated using manufacturer capacity estimates (APS, 2008). Hours of operation, motor size, and nominal efficiency were combined to calculated energy used for feed delivery.

2.2.5 Bedding

Hoop barns for pigs require bedding to effectively operate. Large round bales of cornstalks are the most commonly used bedding for gestation and grow-finish pigs in Iowa. A single bale weighs approximately 544 kg and occupies approximately 2.8 m^2 of area. In Iowa, bedding is baled following corn harvest in October-November and stored for use throughout the year. Usually only bedding that will be exposed to heavy spring and summer rains is stored under shelter (Harmon et al., 2004). Thus for our analysis we assume storage space in hoop barns adequate for 50% of the required bedding for a particular system. Each finishing pig sold will require approximately 91 kg of bedding (Brumm et al., 2004). Each gestation space will require approximately 730 kg of bedding annually (Harmon et al., 2004). The GE of corn stover ranges between 16.7 and 20.9 MJ/kg dry matter (Pordesimo et al., 2005). We assume that baled cornstalks have a moisture content of 15%, thus the GE value of cornstalk bedding used in this analysis is 14.2 MJ/kg of cornstalk bedding. The energy needed to grow corn, bale cornstalks, and deliver bales to the building site is not included in this analysis.

2.2.6 Manure handling

Energy required to remove manure from the production facility is included in this analysis. It was assumed that liquid slurry was agitated and pumped from the storage pits annually. It was assumed that the pump/agitator would require 41 kW and would have a capacity of 7,500 L/min when agitating and 6,500 L/min when pumping slurry from a 2.4 m deep pit. Liquid manure volume was calculated using reference excretion data for different body weights of pigs (ISU, 2003). Water used to clean pig barns ultimately is removed from the building as manure slurry. The volume of wash water for each barn was calculated based on Fulhage and Hoehne (2001). Total manure slurry volume was calculated by combining the volumes of manure and wash water and used to estimate annual energy use for agitating and pumping liquid slurry. A representative tractor-driven slurry pump was selected based on manufacturer literature and interviews with technical support staff. For this analysis we assumed a slurry pump with a capacity of 6500 L/min when pumping and 7,500 L/min when agitating. An appropriately sized diesel tractor was selected to power the slurry agitator using the Nebraska Tractor Test Laboratory database (NTTL, 2008). The tractor identified has an expected fuel efficiency of 16.42 L/hr operation while agitating and pumping liquid manure (NTTL, 2008). Calculated hours of operation were multiplied by fuel use per hour to estimate total fuel use for agitating and pumping liquid manure slurry. Energy used for liquid manure handling was calculated by multiplying the volume of diesel fuel used by an energy value of 38.46 MJ/L (Downs and Hansen, 2007).

Bedded hoop barns are cleaned between groups of pigs using a tractor with mechanical front wheel drive and a front-end loader. For our analysis we assume that the bedding pack is moved from the hoop barn to a compost site within 300 m of the hoop barns. The model assumes the bedding pack in hoop barns for gestating sows is removed twice annually. Hoop barns for grow-finish pigs are typically cleaned out and re-bedded between each group of pigs and that is what our model assumes. Based on our experience a 21.9 × 9.1 m bedded hoop barn can be cleaned and re-bedded in 2 hr if the removed bedding is stored on site. Tractors used to clean hoop barns typically have mechanical front-wheel drive and a power take-off that delivers a maximum power of 48-63 kW. The John Deere 6120 meets those specification (NTTL, 2008). When cleaning a hoop-barn, maximum tractor power is not required for the entire time, thus to calculate fuel use, reported fuel consumption for the John Deere 6120 operating at 83% of maximum power (16.42 L/hr) was used (NTTL, 2008).

After removal from the pig production facility, liquid pig manure is typically injected into crop fields. Energy is required to transport the manure from pig facilities to fields and to incorporate the manure into the soil. These uses of energy are beyond the scope of this paper and are not included in the analysis. The bedding pack from hoop barns is often composted on site to reduce bulk before incorporation into crop fields. Mechanical turning of composting materials assists in the composting process. Finished compost is spread across the surface of crop fields and often incorporated. Turning, spreading, and incorporating compost requires energy but is not included in this analysis because it occurs outside of the pig production facility.

2.2.7 Demonstrated performance differences

The efficacy of converting feed into pork is affected by housing conditions. Because feed is by far the largest source of operating energy it is important to consider feed use by pigs raised in different types of facilities. In a 3-year study in Iowa, Honeyman and Harmon (2003) compared growth and performance of grow-finish pigs housed in bedded hoop barns and conventional confinement. During summer (June through October) gain-to-feed was not different for the two systems but during winter (December through April) pigs housed in deep bedded hoop barns required 8.2% more feed per unit of gain (Honeyman and Harmon, 2003). Based on historic climate data for Iowa, it is estimated that for approximately 40% of the year (146 d) temperatures are sufficiently cold (≤ 7°C) to require more feed per unit of gain in bedded hoop barns compared to conventional systems (Kjelgaard, 2001; ISU, 2008). During other days of the year feed consumption is identical for pigs housed in bedded hoop barns and conventional finishing buildings. Feed use for grow-finish pigs in hoop barns was calculated to be 103.3% of conventional grow-finish feed use or 317.6 kg/market pig. Because identical farrowing and nursery facilities are used by both systems, feed consumption by lactating sows and nursery pigs in the hoop-based system is identical to the conventional system or 15.6 and 51.0 kg of feed per market pig, respectively.

Annual feed use for gestating sows housed in hoop barns was assumed to be 7% more than feed use by gestating sows in conventional confinement facilities (Lammers et al., 2008a). Reproductive performance of group housed sows in hoop barns is equal to sows housed in individual gestation stalls and for some measures may be improved (Lammers et al., 2007). Sows housed in hoop barns for gestation gave birth to 7.5% more live pigs per litter and had equal pre-wean mortality rates as sows house in individual gestation stalls (Lammers et al., 2007). Originally it was assumed that prolificacy and sow inventory would be identical for the two systems (Lammers et al., 2009). Taking into consideration the demonstrated differences in prolificacy, fewer sows are needed in the hoop barn-based system. A hoop barn-based production system with 7.5% greater sow prolificacy compared to conventional confinement sows would require 45 vs 48 and 130 vs 140 farrowing crates to produce 5,200 and 15,600 market pigs. Similarly gestation spaces required for the hoop systems is 288 (8 hoop barns) and 838 (23 hoop barns) vs 310 and 900 individual gestation stalls. Gestating sow feed consumption per litter in bedded hoop barns was estimated as 107% of gestating sow feed use in the conventional system, but 7.5% more pigs per litter are assumed to be marketed from sows gestated in hoop buildings. Taking into consideration these performance differences, gestation feed per market pig sold from the hoop barn-based system is equal to or slightly less than gestation feed per market pig sold from the conventional system. We assume feed that gestation feed per market pig sold for both systems is 37.0 kg. Each market pig in the conventional system was attributed 411.1 kg of feed. When performance differences were included in the analysis, each, market pig in the hoop barn-based system was attributed 421.2 kg of feed. Taking into account demonstrated performance differences (Honeyman and Harmon, 2003; Lammers et al., 2007), farrow-to-finish swine farms using bedded hoop barns for gestating sows and grow-finish pigs require approximately 2.4% more feed annually than conventional systems.

Because fewer hoop barns were needed for gestating sows in the second analysis, bedding use and energy required to remove bedding and manure pack was adjusted accordingly. Energy use for heat lamps in the farrowing facility was also reduced to match the number of sows in farrowing crates for the hoop barn-based system. Modeled energy use for ventilation and heating of the farrowing barn in the hoop barn-based system was either less than or equal to the conventional system. Because the reduction in modeled energy use for ventilation and heating was very small, no adjustments were made for these parameters.

2.3 Energy type and greenhouse gas emission

Energy comes from several fuels. Operating energy for mechanical control of the thermal environment, water, lights, feed, bedding, and manure handling values were calculated and then divided by fuel type. Emissions of three greenhouse gases— CO_2, CH_4, and N_2O — were estimated based on fuel type (IPCC, 2006; EPA, 2008). Standardized global warming potentials for the three gases of interest (IPCC, 2007) were used to calculate emission of CO_2 equivalents or operating carbon by fuel type. Operating energy and carbon were then totaled for each system considered.

There are two main categories considered in this analysis: renewable and nonrenewable. It is generally accepted that nonrenewable fuels require long periods of time to form and that reserves are being used faster than the rate of formation. Alternatively renewable fuels are fuels that are consumed at rates similar to their rate of regeneration. In our analysis there are 3 types of nonrenewable energy: electricity, liquefied petroleum gas, and diesel. Electricity is not inherently nonrenewable, for example electrical generation using wind turbines is growing in Iowa and is generally considered a renewable source of electricity. However, more than 75% of electricity in Iowa is produced by burning coal (EIA-

DOE, 2009) and coal is indisputably a nonrenewable fuel. Similarly there has been rapid growth in production and use of biodiesel—monoakyl esters derived from vegetable oils or animal fats rather than petroleum. Biodiesel is typically considered a renewable fuel, but the majority of diesel used in Iowa is petroleum based which is nonrenewable. In this analysis the category renewable fuel refers exclusively to sources of energy that can be regenerated annually. Feed and bedding are produced from annual crops in Iowa and are the two types of fuel included in the renewable energy category.

2.3.1 Nonrenewable fuels

In this analysis electricity is used for pumping water, air exchange, moving feed from storage to feeders, illumination, auxiliary heat lamps in the farrowing barn, and similar activities. Domestic electricity generation emission factors are available for Iowa (EPA, 2008). It is calculated that 229.32 kg of CO_2 equivalents are released for every GJ of electrical energy used (IPCC, 2006, 2007; EPA, 2008).

Liquefied petroleum (LP) gas is commonly used to heat pig facilities in Iowa. In our analysis, energy used for heating pig facilities will originate from liquefied petroleum gas. It is calculated that 63.52 kg of CO_2 equivalents are released for every GJ of energy that originates from liquefied petroleum gas (IPCC, 2006, 2007).

Diesel fuel is a common source of mobile energy on Iowa farms. Energy used for handling manure and heating wash water is assumed to originate from diesel fuel. It is calculated that 82.73 kg of CO_2 equivalents are released for every GJ of energy that originates from diesel fuel (IPCC, 2006, 2007).

2.3.2 Renewable fuels

Most feed and all bedding material comes from annual plants and are considered renewable fuels in this analysis. The GE of feed and bedding delivered to pigs is the potential renewable energy consumption of a given facility. Because feed and bedding originate from annual plants, no net CO_2 emissions are associated with these forms of energy in this analysis.

Renewable fuels are further divided between energy that is directly consumed (feed) and energy that is recycled (bedding). Swine feed is consumed by pigs and converted to meat and other tissue. Metabolism is not 100% efficient and some of the energy delivered as feed is lost in manure, urine, and gaseous emissions. The GE of feed eaten by pigs is irretrievably transformed and so it is truly consumed energy. Alternatively, cornstalks used for bedding are not significantly altered in form. Pigs use bedding for lounging, dunging, and controlling their thermal climate. Little bedding is eaten by pigs and so the mass of bedding that enters a hoop barn is later removed with additional mass (and energy) from urine and feces. Generation of energy from combustion of corn stalks in Iowa is very small and most corn stalks are simply returned to the soil following harvest. Cornstalks used for bedding are also ultimately returned to cropland, and so any energy found in cornstalk bedding is not consumed but rather recycled back to cropland after a short (≤ 1 yr) delay. Because the boundary of this analysis is strictly drawn around the pig production facility, implications of this delayed return of cornstalks to cropland are beyond the scope of this paper.

2.3.3 Production Outputs

Swine production systems transform non-renewable and renewable streams of energy into meat and other tissue. The efficiency of this conversion is not 100%. Raising pigs results in the co-generation of feces, urine, and gaseous emissions. This analysis examines energy use on a market pig basis. The consumed energy that is returned as tissue and lost as feces, urine, and gaseous emissions from a single pig raised in the conventional system and the hoop barn-based alternative is assumed to be equal.

3. Results

3.1.1 Embodied energy

Embodied energy of different types and scales of swine production facilities are presented in table 6. Grow-finish and gestation facilities are different for the two systems and are detailed in table 6. Nursery facilities are identical for both conventional confinement and hoop barn-based systems(Lammers et al., 2009). Farrowing facilities are very similar, the only difference being that in the conventional confinement system, manure from the farrowing facility is stored underneath the gestation barn and in the hoop barn-based system that uses bedded hoop barns for gestation a separate liquid manure storage tank is required for the farrowing facility (Lammers et al., 2009). Because the farrowing and nursery facilities are similar for both pig production systems they are not detailed in this analysis. Embodied energy of the farrowing, nursery, and bedding storage facilities are included in the systems total reported in table 6.

Concrete is the largest component of embodied energy in all grow-finish facilities, accounting for 45–57% of the total embodied energy in grow-finish buildings. Steel is the second largest component of embodied energy in grow-finish buildings. In conventional confinement facilities, as scale of production increases, embodied energy per market pig decreases. Steel is an exception to this trend. This results from differences in building dimensions and layout presented by Lammers et al. (2009). The 5,200 market pig system assumes one 92.0 × 15.5 m building with 4 rooms for grow-finish. The 15,600 market pig system assumes four 61.3 × 15.5 m buildings with each building managed as one room. The difference in building number and dimensions results in more concrete reinforcing steel per market pig needed in the conventional grow-finish buildings scaled to produce 15,600 market pigs annually.

Using hoop barns for grow-finish pigs requires approximately 50% less embodied energy compared to conventional confinement buildings. In this analysis increasing the hoop barn-based system from 5,200 to 15,600 market pigs annually increases the embodied energy per market pig produced. This is because of differences in grow-finish hoop barn organization (Lammers et al., 2009). As described by Lammers et al. (2009)the system scaled to produce 5,200 market pigs annually requires eight 21.9 × 9.1 m hoop barns. These 8 hoop barns share one common sort/load area. Alternatively in the 15,600 market pig system, twenty-four, 21.9 × 91 m hoop barns are arranged in 4 groups of 6 hoop barns and each group requires a separate sort/load area (Lammers et al., 2009). These arrangements were selected to best match the housing situation for the conventional confinement system (Lammers et al., 2009).

Within a system, increasing from 5,200 to 15,600 market pigs has little effect on the embodied energy of grow-finish facilities. Within a system there was an advantage to increasing scale in gestation facilities. Gestation facilities systems scaled to produce 15,600 market pigs annually require 8–12% less embodied energy per market pig compared to gestation facilities scaled to produce 5,200 market pigs annually. Steel is the largest source of embodied energy in gestation buildings due to the use of gestation crates or feeding stalls in both conventional and hoop barn gestation facilities. Conventional gestation requires about 40% more embodied energy as steel than hoop barns. Hoop barns require more lumber and more thermoplastics, but require 13–17% less total embodied energy per market pig compared to conventional confinement.

Farrowing and nursery facilities use large quantities of thermoplastics and thermoplastics require a tremendous amount of embodied energy. This results in the dramatic increase in embodied energy found in thermoplastics of the all buildings section (table 6). Within a system type, increasing the scale of production by 300% does not decrease the embodied energy per market pig by 33%. Rather a 15% reduction is found in the conventional facilities and a 24% decrease is estimated for the hoop barn-based system. The hoop barn-based system scaled to produce 15,600 market pigs annually requires the least embodied energy per market pig of any system considered. Tripling pig production reduces embodied energy per market pig by 24% in the hoop barn-based system, but only 15% in the conventional confinement system. The embodied energy per market pig of a hoop barn-based facility complex sized to produce 5,200 market pigs annually is 6.8% more than the embodied energy of a conventional confinement facility sized to produce 15,600 market pigs annually. Producing 15,600 or 5,200 pigs using hoop barns for gestation and grow-finish requires 1,393.8 and 1,064.1 MJ of embodied energy per market pig sold. The embodied energy of conventional confinement facilities sized to produce 15,600 and 5,200 market pigs annually is 1,304.5 and 1,543.0 MJ per market pig sold.

3.1.2 Embodied carbon

Embodied carbon of different types and scales of pig facilities are reported in table 7. Embodied carbon follows the same pattern of embodied energy—hoop barn-based facilities require less embodied carbon than conventional facilities and increasing the scale of production reduces embodied carbon per market pig. Although the conventional confinement system sized to produce 15,600 market pigs annually required slightly less embodied energy per pig space than the hoop barn-based facility sized to produce 5,200 market pigs annually, the embodied carbon was less for the hoop barn-based facility. Producing pigs in hoop barn-based facilities sized to produce 15,600 or 5,200 pigs annually results in one-time embodied CO_2 emissions equal to 80.6 and 93.7 kg per market pig sold. Building conventional confinement facilities producing 15,600 or 5,200 market pigs annually result in CO_2 emissions of 100.9 and 113.4 kg per market pig sold.

3.1.3 Annual embodied energy and carbon during useful life of facilities

Table 8 compares annual embodied energy and carbon of all buildings under 15 and 20-year useful lifespan scenarios. On a useful lifespan basis, the embodied energy and carbon of pig facilities follow the same pattern as total embodied energy and carbon. Adding replacement tarps into the analysis increases the embodied energy and the hoop barn-based system. The overall advantage of hoop barn-based facilities sized to produce 15,600 market pigs annually is maintained in spite of this increase. Because the embodied carbon of replacement tarps is so small relative to other facility components, the embodied carbon of the hoop barn-based system did not change. Hoop barn-based facilities sized to produce 5,200 market pigs annually require greater embodied energy, but less embodied carbon per market pig than conventional confinement facilities sized to produce 15,600 market pigs. The conventional confinement facility sized to produce 5,200 pigs annually requires the most embodied energy and carbon per market pig of all facility types examined.

3.2.1 Operating energy

Mason City, 43.1°N, 93.2°W, shares a latitude that is similar to 6 of the top 10 pig producing counties in Iowa (USDA, 2002a). In Iowa, latitude is more predictive of thermal environment than longitude and so Mason City was selected as most representative of climatic conditions experienced by pig farms in Iowa. The estimated energy use by pig space for thermal environment control of different phases and scales of conventional confinement facilities located near Mason City Iowa is presented as table 9. Providing adequate heat accounts for 78–93% of the estimated energy use for thermal environment control in pig barns. Increasing from 5,200 to 15,600 market pigs annually reduces energy use per pig space by 1–7% for different production phases.

Thermal control of farrowing facilities requires nearly 700% more energy per pig space than any other production facility. Farrowing buildings must be kept at higher temperatures than other buildings to meet the thermal needs of young pigs. Farrowing buildings also have less density of pig spaces than other building types. Conventional confinement gestation facilities are estimated to use more energy per pig space than nursery and grow-finish facilities but less than farrowing barns. Providing heat is the major use of energy for thermal control of conventional pig facilities for all production phases in Iowa. As growing pigs increase in size, less energy is used for heating buildings and more is used for ventilation. Approximately 93–97% of the energy use for thermal control of farrowing barns is associated with providing heat. Alternatively, 80% of the energy use for thermal control of grow-finish buildings results from providing heat.

Table 10 details the operating energy for different types and scales of pig production facilities by fuel type and activity when feed conversion and reproductive performance are identical for the two systems. Liquefied petroleum gas for heating pig buildings is the single largest nonrenewable energy input for conventional systems. The hoop barn-based system uses 35% less energy as liquefied petroleum gas compared to conventional systems. Hoop barns do not use mechanical systems to provide heat, but use bedding packs. Removal of bedding packs with a front-end loader occurs between every group of grow-finish pigs, or 3.3 times per year in our analysis. Liquid manure storage pits typical of conventional systems are usually designed to store manure slurry for a year. Our analysis assumes liquid manure pits are pumped annually. This results in more time, and ultimately more diesel fuel use for removing bedding pack in the hoop barn-based system as compared to pumping liquid manure in the conventional system.

The hoop barn-based systems uses 70% less energy for ventilation, pressure washing, illumination, feed delivery, and heating of wash water that identically scaled conventional facilities require to operate. Despite using nearly 4 times more energy for manure handling, the hoop barn-based systems uses 36% less total nonrenewable energy to produce market pigs than the conventional system. On a per pig basis, the hoop barn based system producing 15,600 market pigs annually uses the least nonrenewable energy. The hoop barn system producing 5,200 market pigs annually uses 40% of the nonrenewable energy than the conventional system scaled to produce 15,600 market pigs annually requires. The conventional system producing 5,200 market pigs annually requires the most nonrenewable energy per market pig. In the hoop barn-based systems, increasing the number of pigs marketed reduces the nonrenewable energy used by 4%. In the conventional systems, increasing the number of pigs marketed reduces the nonrenewable energy used by 6%.

The amount of renewable energy—feed and bedding—used to operate pig facilities dwarfs the nonrenewable energy inputs. Energy in feed is by far the largest single contributor to operating energy in all pig production systems examined. No bedding is used in conventional facilities, but bedding is a critical component of managing pigs in hoop barns.

Our analysis assumes 100% of energy present in bedding entering hoop barns is returned when hoop barns are cleaned out. The hoop barn-based system uses similar amounts (2% less) of total energy as the conventional system. This is because of the overwhelming impact of feed energy to the overall energy consumption total.

Increasing pig production by three-fold barely changes total energy use per pig (0.05–0.2%) in both systems. Once again the influence of renewable energy, particularly feed on the total energy budget of pig production is responsible for the similarity between systems producing 5,200 market pigs and systems scaled to produce 15,600 market pigs annually. From a total operating energy consumption per market pig produced standpoint, there is little if any inherent energetic advantage in increasing the scale of pig production.

Table 11 presents type of fuel inputs for different phases of production. Because the farrowing and nursery facilities are operated the same way under hoop barn-based and conventional confinement systems, the operating energy for farrowing and nursery facilities are identical at a given level of production. Approximately 67% of the nonrenewable energy used in farrowing facilities is electricity, primarily because of heat lamps. Liquefied petroleum gas accounts for 56–58% of the nonrenewable energy use in nursery buildings. In conventional grow-finish buildings liquefied petroleum gas is the largest nonrenewable energy source. As expected diesel fuel use mirrors manure production—grow-finish pigs produce the most manure of any phase of production and use the most diesel fuel of all phases. Other than diesel fuel to clean out bedding packs, there is very little nonrenewable energy used in hoop barns for grow-finish pigs and gestating sows. A large portion (67%) of nonrenewable energy use in conventional confinement facilities for grow-finish pigs and gestating sow is used to heat buildings.

As expected renewable energy use is highest in the grow-finish phase because of the large quantities of feed that is consumed by pigs in this phase. In hoop barns, 21% of renewable energy input in the grow-finish phase is bedding. Gestating sows are limit fed and in gestation hoop barns 50% of total renewable energy input is bedding. Conventional systems do not use bedding and so feed accounts for 100% of renewable energy in those systems. The grow-finish phase of pig production is the most energetically intensive, however the other phases cannot be entirely ignored. Approximately 30% of the nonrenewable energy use occurs in the farrowing and nursery stages of production and gestation buildings account for 23% of total nonrenewable energy use in conventional systems. In hoop barn-based systems farrowing and nursery accounts for 59 and 20%of nonrenewable energy use, respectively. Gestation accounts for only 9% of nonrenewable energy consumption in hoop barn-based pig production. Regardless of system, focusing only on the grow-finish phase ignores large amounts of nonrenewable energy use that may be important to consider when estimating greenhouse gas emissions associated with pig production.

3.2.2 Greenhouse gas emissions

Greenhouse gas emissions from operation of different phases of pig production within different types and scales of facilities are presented as table 12. Because feed and bedding originate from annual plants, no net CO_2 emissions are associated with these forms of energy in this analysis. Using hoop barns for gestation and grow-finish reduces greenhouse gas emissions per market pig by more than 50%. Producing 15,600 market pigs annually using hoop barn-based facilities results in emission of 10.97 kg of CO_2 equivalents per market pig. Producing only 5,200 market pigs annually using hoop barn-based facilities increases the greenhouse gas emissions per market pig sold by 6.9% to an average of 11.73 kg greenhouse gas emissions per market pig. Producing market pigs in conventional confinement facilities requires greater use of electricity, liquefied petroleum gas, and diesel fuel. This in turn translates into larger greenhouse gas emissions from operation of those facilities. Increasing the number of market pigs produced from 5,200 to 15,600 results in 5.7% less greenhouse gas emissions per market pig sold from conventional confinement facilities. However using conventional confinement facilities to produce 15,600 market pigs annually results in 48% more greenhouse gas emissions per market pig sold compared to producing 5,200 market pigs annually using hoop barn-based facilities.

3.2.3 Incorporating demonstrated performance differences

Table 13 presents performance adjusted operating energy and associated greenhouse gas emissions of different pig production systems and scales by fuel type and activity. With 7.5% more pigs per sow in the hoop barn-based system, fewer sows must be maintained in gestation and fewer litters need to be farrowed. This results in reductions in the amount of electricity used for heat lamps in the farrowing facility and in diesel fuel used for cleaning out hoop barns for gestating sows. Under this analysis, hoop barn-based pig production uses 37–39% less nonrenewable energy than conventional systems.

Our second analysis assumes that grow-finish pigs housed in bedded hoop barns require 3.3% more feed per unit of gain, this translates into the 3% increase in renewable energy as feed for the entire pig herd presented for hoop barn-based pig production in table 13. Because of increase feed consumption during the grow-finish phase of production, systems using hoop barns for gestation and grow-finish at the two scales examined require similar amounts (2% more) of operating energy/market pig as the conventional systems.

Incorporating improved sow reproduction reduces nonrenewable energy use for hoop barn-based pig production and reduces emission of greenhouse gases. Under the assumption of different performance between two general pig production systems, hoop-barn based production results in 54–57% less greenhouse gas emission. The optimal system for producing pigs in terms of minimizing greenhouse gas emissions is the hoop barn-based system scaled to sell 15,600 market pigs annually. The conventional system scaled to produce 5,200 market pigs annually uses the most nonrenewable energy of any system examined and consequently emits the most greenhouse gas.

4.0 Discussion

Producing pigs using hoop barns for grow-finish and gestation requires less embodied energy and carbon than using conventional confinement facilities. Hoop barn-based pig production require similar quantities of total operating energy than conventional facilities but results in less greenhouse gas emissions per market pig. Increasing the scale of production from 5,200 to 15,600 market pigs annually lowers the embodied energy, embodied carbon, nonrenewable energy use and greenhouse gas emissions per market pig. However the reduction is less dramatic for the hoop barn-based system compared to the conventional confinement system. Hoop barn-based production scaled to produce 5,200 market pigs annually requires similar amounts of embodied energy and less embodied carbon compared to conventional confinement facilities scaled to produce 15,600 market pigs annually. Using hoop barns for grow-finish and gestation requires less nonrenewable energy and results in lower emissions of greenhouse gas.

This analysis demonstrates that hoop barns for pigs have several energetic and environmental advantages over conventional confinement facilities. Embodied energy and carbon values are heavily dependent on the assumptions that are included in their calculation. Using one database that includes all materials (Hammond and Jones, 2008) insures that materials are compared on an equal basis. The listed values of embodied energy and carbon for different pig production facilities may or may not be exact. However the relative magnitude of the values, particularly when comparing different systems built and operated at the same location, is expected to remain stable. Similarly operating energy use and the thermal environment regime of a particular pig facility will depend on climate conditions. The conditions assumed in this analysis are typical of historic averages for Iowa, the leader in United States pig production. It is representative of the environment where the majority of pigs in the United States are raised.

Hoop barn-based pig production is more dependent on operating energy from feed and bedding than conventional confinement production. Alternatively conventional confinement facilities rely more on nonrenewable fossil fuels to modify pig environment. Hoop barns for grow-finish pigs and gestating sows have been successfully demonstrated and performance of pigs in these facilities are similar to pigs in conventional confinement (Honeyman and Harmon, 2003; Lammers et al., 2007). Historically the availability of fossil fuels has minimized pressure to critically consider all uses of energy in pig production. Rising energy prices, global conflicts, and recognition of the environmental impacts of using fossil fuels are increasing awareness and incentive to optimize use of these limited resources. Using hoop barns for grow-finish pigs and gestating sows is an effective strategy to reduce direct use of fossil fuels for pork production and may minimize global climate altering emissions.

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Table 1. Density, embodied energy, and embodied carbon for building materials examined[a]

Material	Density, g/cm^3	Embodied energy, MJ/kg	Embodied carbon, kg CO_2/kg
Concrete	2.40	0.95	0.129
Steel	8.08	24.40	1.770
Lumber	0.53	7.40	0.450
Thermoplastics	0.95	76.70	1.600
Cellulose insulation	0.03	2.12	0.000

[a] From Hammond and Jones (2008).

Table 2. Pig facility assumptions[a]

Production Phase	Scale, market pigs/yr	Building dimensions, m × m	Area/thermal resistance, MJ/hr-°C	Stocking rate, hd/barn	Number of buildings for production system
Farrowing	5,200	21.9 × 13.4	0.56	48	1
Nursery	5,200	30.5 × 15.5	0.79	880	1
Grow-Finish	5,200	92.0 × 15.5	6.38	1,600	1
Gestation	5,200	52.4 × 13.4	3.72	310	1
Farrowing	15,600	73.2 × 13.4	1.55	140	1
Nursery	15,600	41.1 × 15.5	1.01	1,300	2
Grow-Finish	15,600	61.3 × 15.5	4.43	1,200	4
Gestation	15,600	70.3 × 13.4	4.78	450	2

[a] From (Lammers et al., 2009)

Table 3. Building occupancy, pig size and heat production, target temperature and minimum ventilation rate assumptions for estimating energy use for thermal climate control of conventional swine facilities

Building	Occupancy				Room Temperature[a]		Ventilation rate[b]	
	Pigs in hr/yr	Pigs out, Hr/yr	Pig body weight, kg	Sensible heat[c], kJ/pig	Min, °C	Max, °C	Minimum[d], $L \times min^{-1} \times hd^{-1}$	Maximum[e], $L \times min^{-1} \times hd^{-1}$
Farrowing[f]	7,447	1,314	142.9	897.9	18.3	21.1	566	14,158
Nursery	7,896	964	18.8	188.4	19.5	25.5	85	991
Grow-finish	8,672	88	85.3	531.4	15.5	22.5	283	3,398
Gestation	8,760	0	157.0	598.2	12.8	21.1	396	4,248

[a] Based on Holden et al. (1996), Carr (1998), and Wathes and Whittemore (2006). Min and max is the temperature at which heat must be added or removed, respectively, to maintain pig comfort and performance.

[b] From MWPS (1990b).

[c] Calculated based on Pedersen (2002) and Brown-Brandl et al. (2004).

[d] Minimum ventilation rate to maintain acceptable air quality and humidity inside building.

[e] Maximum allowed ventilation rate, coupled with additional cooling strategies to reduce interior temperature of building

[f] Lactating sows will be housed in the farrowing facility with their litter of pigs. Presented body weight and sensible heat production is for the sow only.

Table 4. Water use by pig facilities

Facility	Drinking and cooling[a]	Cleaning[b]
Farrowing	30 L × head-1×d-1	1,083 L × space^{-1} × yr^{-1}
Nursery	5 L × head^{-1} × d^{-1}	60 L × space^{-1} × yr^{-1}
Grow-finish	10 L × head-1×d-1	137 L × space^{-1} × yr^{-1}
Gestation	16 L × head-1×d-1	138 L × space^{-1} × yr^{-1}

[a] Based on Thacker (2001).
[b] From Fulhage and Hoehne (2001).

Table 5. Daily feed intake and growth efficiency assumptions for pigs housed in conventional confinement[a]

Class of pig	Body weight	Feed level
Gestating sow	157.0 kg	2.3 kg/d
Lactating sow	142.9 kg	6.4 kg/d
Growing pigs	5–23 kg	1.7 kg of feed/kg of body weight gain
	23–45 kg	2.0 kg of feed/kg of body weight gain
	45–91 kg	2.6 kg of feed/kg of body weight gain
	91–136 kg	3.4 kg of feed/kg of body weight gain

[a] Based on work reported by Lammers et al. (2007) and Lammers et al. (2008b).

Table 6. Embodied energy of pig facilities per market pig by system and scale

System	Conventional		Hoop barn-based	
Market pigs/yr	5,200	15,600	5,200	15,600
Grow-finish, MJ/market pig				
Concrete	226.0	209.2	123.8	126.3
Steel	134.8	177.2	51.7	52.1
Lumber	47.7	42.7	26.3	26.6
Thermoplastics	45.4	23.6	15.8	15.8
Insulation	2.7	2.4	0	0
Diesel	5.9	5.3	0	0
Total	462.5	460.4	217.7	220.8
Gestation, MJ/market pig				
Concrete	127.3	104.1	110.8	102.5
Steel	179.8	167.6	128.3	118.8
Lumber	18.7	16.5	23.8	22.2
Thermoplastics	10.4	7.9	20.0	18.5
Insulation	1.3	1.2	0	0
Diesel	2.1	1.2	0	0
Total	339.6	298.5	282.9	262.0
All buildings, MJ/market pig				
Concrete	433.5	388.5	350.2	329.2
Steel	538.1	496.1	422.7	347.1
Lumber	79.8	71.7	64.0	61.6
Thermoplastics	472.1	331.7	547.5	318.7
Insulation	7.9	6.9	3.8	3.3
Diesel	11.6	9.6	5.6	4.2
Total	1,543.0	1,304.5	1,393.8	1,064.1

Table 7. Embodied carbon of pig facilities per market pig by system and scale

System	Conventional		Hoop barn-based	
Market pigs/yr	5,200	15,600	5,200	15,600
Grow-finish, kg CO_2/market pig				
Concrete	30.8	28.4	16.7	17.2
Steel	9.8	12.8	3.8	3.8
Lumber	2.9	2.6	1.5	1.6
Thermoplastics	1.0	0.5	0.4	0.3
Diesel	0.5	0.4	0	0
Total	45.0	44.7	22.4	22.9
Gestation, kg CO_2/market pig				
Concrete	17.3	14.2	15.0	13.9
Steel	13.1	12.2	9.2	8.8
Lumber	1.2	1.0	1.5	1.3
Thermoplastics	0.2	0.2	0.4	0.4
Diesel	0.2	0.1	0	0
Total	32.0	27.7	26.1	24.4
All buildings, kg CO_2/market pig				
Concrete	58.8	52.8	47.5	44.7
Steel	39.0	36.0	30.6	25.2
Lumber	4.8	4.4	3.8	3.7
Thermoplastics	9.8	6.9	11.3	6.7
Diesel	1.0	0.8	0.5	0.3
Total	113.4	100.9	93.7	80.6

Table 8. Annual allotment of embodied energy and carbon for different lifespan scenarios of different pig facilities by system and scale

System	Conventional		Hoop barn-based	
Market pigs/year	5,200	15,600	5,200	15,600
Embodied energy, MJ/market pig				
15 year useful life	102.9	87.0	93.0	75.7
15 year useful life, replace thermoplastic tarps once			95.3	73.2
20 year useful life	77.2	65.2	69.7	53.2
20 year useful life, replace thermoplastic tarps once			71.5	54.9
Embodied carbon, kg/market pig				
15 year useful life	7.6	6.7	6.2	5.4
15 year useful life, replace thermoplastic tarps once			6.3	5.4[a]
20 year useful life	5.7	5.0	4.7	4.0
20 year useful life, replace thermoplastic tarps once			4.7[a]	4.1

[a] In some case, the embodied carbon of additional thermoplastic tarps is so small relative to other facility components replacing the thermoplastic tarps does not impact embodied carbon per market pig.

Table 9. Energy use per pig space for thermal environment control of different phases and scales of conventional confinement facilities in Mason City, Iowa[a]

Barn	Scale, market pig/yr	Pig spaces	Ventilation, MJ/space	Heat, MJ/space	Auxiliary Heat, MJ/space	Total, MJ/space
Farrowing	5,200	48	114.6	1,433.3	2,737.5	4,285.4
Nursery	5,200	880	16.0	246.0	0	262.0
Grow-finish	5,200	1,600	37.5	230.0	0	267.5
Gestation	5,200	310	144.2	1,175.5	0	1,319.7
Farrowing	15,600	140	188.6	1,378.6	2,737.5	4,304.7
Nursery	15,600	2,600	15.4	226.4	0	241.8
Grow-finish	15,600	4,800	35.0	210.5	0	245.5
Gestation	15,600	900	144.4	1,112.6	0	1257.0

[a] Mason City, 43.1°N, 93.2°W

Table 10. Operating energy of different systems and scales of pig facilities by fuel type and activity[a]

System	Conventional		Hoop barn-based	
Market pigs per year	5,200	15,600	5,200	15,600
Nonrenewable energy, MJ/market pig				
Electricity				
Ventilation	26.9	26.6	5.3	5.1
Auxiliary heat	25.3	24.6	25.3	24.6
Water delivery	2.6	2.5	2.6	2.4
Pressure washing	3.4	3.3	0.9	0.9
Illumination	6.5	5.9	3.8	3.7
Feed delivery	2.6	1.0	0.2	0.3
Liquefied petroleum gas				
Building heat	109.7	102.9	72.9	66.8
Diesel fuel				
Heating wash water	16.8	15.9	4.6	4.4
Manure handling	2.9	2.7	11.1	10.8
Total nonrenewable energy	196.7	185.4	126.7	119.4
Renewable energy, MJ/market pig				
Feed	6,534.4	6,534.4	6,534.4	6,534.4
Bedding into barn	0	0	1,910.2	1,890.2
Bedding removed from barn			(1,910.2)	(1,890.2)
Net renewable energy	6,534.4	6,534.4	6,534.4	6,534.4
Total energy, MJ/market pig	6,731.1	6,719.8	6,661.1	6,653.8

[a]Feed conversion and reproductive performance identical for both systems.

Table 11. Energy inputs for different phases of pig production by system, phase, and scale of facilities[a]

	Nonrenewable Energy, MJ/market pig				Renewable Energy, MJ/market pig		
	Electricity	LP Gas	Diesel	Total	Feed	Bedding	Total
Conventional confinement; 5,200 market pigs annually							
Farrowing	29.5	12.2	2.5	44.2	248.0	0	248.0
Nursery	4.0	8.9	2.5	15.4	820.8	0	820.8
Grow-finish	21.7	56.9	12.1	90.7	4,875.2	0	4,875.2
Gestation	12.2	31.5	2.7	46.4	590.4	0	590.4
Conventional confinement; 15,600 market pigs annually							
Farrowing	28.7	12.2	2.5	44.2	248.0	0	248.0
Nursery	3.9	8.1	2.4	14.4	820.8	0	820.8
Grow-finish	19.5	54.5	11.3	85.3	4,875.2	0	4,875.2
Gestation	11.6	28.7	2.6	42.9	590.4	0	590.4
Hoop barn-based; 5,200 market pigs annually							
Farrowing	29.5	12.2	2.5	44.2	248.0	0	248.0
Nursery	4.0	8.9	2.5	15.4	820.8	0	820.8
Grow-finish	2.2	0	6.4	8.6	4,875.2	1,292.2	6,167.4
Gestation	2.4	0	4.4	6.8	590.4	618.0	1,208.4
Hoop barn-based; 15,600 market pigs annually							
Farrowing	28.7	12.2	2.5	44.2	248.0	0	248.0
Nursery	3.9	8.1	2.4	14.4	820.8	0	820.8
Grow-finish	2.0	0	6.4	8.4	4,875.2	1,292.2	6,167.4
Gestation	2.3	0	4.0	6.3	590.4	598.0	1,188.4

[a]Feed conversion and reproductive performance identical for both systems.

Table 12. Greenhouse gas emissions from operation of different systems and phases of pig production within different types and scales of facilities[a]

	Electricity kg CO_2 / market pig	LP Gas, kg CO_2 / market pig	Diesel, kg CO_2 / market pig	Total, kg CO_2 / market pig
Conventional confinement; 5,200 market pigs annually				
Farrowing	6.76	0.77	0.21	7.74
Nursery	0.92	0.56	0.21	1.69
Grow-finish	4.98	3.61	1.00	9.59
Gestation	2.80	2.00	0.22	5.02
Total	15.46	6.94	1.64	24.04
Conventional confinement; 15,600 market pigs annually				
Farrowing	6.58	0.74	0.20	7.52
Nursery	0.89	0.51	0.20	1.60
Grow-finish	4.47	3.46	0.93	8.86
Gestation	2.66	1.82	0.22	4.70
Total	14.60	6.53	1.55	22.68
Hoop barn-based; 5,200 market pigs annually				
Farrowing	6.76	0.77	0.21	7.74
Nursery	0.92	0.56	0.21	1.69
Grow-finish	0.50	0	0.53	1.03
Gestation	0.55	0	0.36	0.91
Total	8.74	1.33	1.31	11.73
Hoop barn-based; 15,600 market pigs annually				
Farrowing	6.58	0.74	0.20	7.52
Nursery	0.89	0.51	0.20	1.60
Grow-finish	0.46	0	0.53	0.99
Gestation	0.53	0	0.33	0.86
Total	8.46	1.25	1.26	10.97

[a]Feed conversion and reproductive performance identical for both systems.

Table 13. Performance adjusted[a] operating energy and associated greenhouse gas emissions of different pig production systems and scales by fuel type and activity

System	Conventional		Hoop barn-based	
Market pigs per year	5,200	15,600	5,200	15,600
Nonrenewable energy, MJ/market pig				
Electricity				
Ventilation	26.9	26.6	5.3	5.1
Auxiliary heat	25.3	24.6	23.7	19.8
Water delivery	2.6	2.5	2.6	2.4
Pressure washing	3.4	3.3	0.9	0.9
Illumination	6.5	5.9	3.8	3.7
Feed delivery	2.6	1.0	0.2	0.3
Liquefied petroleum gas				
Building heat	109.7	102.9	72.9	66.8
Diesel fuel				
Heating wash water	16.8	15.9	4.6	4.4
Manure handling	2.9	2.7	10.6	10.5
Total nonrenewable energy	196.7	185.4	124.6	113.9
Renewable energy, MJ/market pig				
Feed	6,534.4	6,534.4	6,729.0	6,729.0
Bedding into barn	0	0	1,866.3	1,849.0
Bedding removed from barn			(1,866.3)	(1,849.0)
Net renewable energy	6,534.4	6,534.4	6,729.0	6,729.0
Total energy, MJ/market pig	6731.1	6,719.8	6,853.6	6,842.9
Greenhouse gas emissions				
Electricity, kg CO_2/market pig	15.46	14.60	8.37	7.38
LP Gas, kg CO_2/market pig	6.94	6.53	1.34	1.25
Diesel, kg CO_2/market pig	1.64	1.55	1.26	1.23
Total emissions, kg CO_2/market pig	24.04	22.68	10.97	9.86

[a]Grow-finish pigs housed in hoop barns consume 3.3% more feed and sow herd reduced by 7% in hoop barn-based system to account for reproductive performance differences.

CHAPTER 5. DIGESTIBLE AND METABOLIZABLE ENERGY OF CRUDE GLYCEROL FOR GROWING PIGS

A paper published in the *Journal of Animal Science*[2]

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ABSTRACT: The apparent DE and ME value of crude glycerol for growing pigs was determined in 5 experiments using crude glycerol (86.95% glycerol) from a biodiesel production facility with soybean oil used as the initial feedstock (AG Processing Inc., Sergeant Bluff, IA). Dietary treatments were 0, 5, or 10% glycerol addition to basal diets in Exp. 1; 0, 5, 10, or 20% glycerol addition to basal diets in Exp. 2; and 0 and 10% crude glycerol addition to the basal diets in Exp. 3, 4, and 5. Each diet was fed twice daily to pigs in individual metabolism crates. After a 10-d adjustment period, a 5-d balance trial was conducted. During the collection period, feces and urine were collected separately after each meal and stored at 0°C until analyses. The GE of each dietary treatment and samples of urine and feces from each pig were determined by isoperibol bomb calorimetry. Digestible energy of the diet was calculated by subtracting fecal energy from the GE in the feed, whereas ME was calculated by subtracting the urinary energy from DE. The DE and ME values of crude glycerol were estimated as the slope of the linear relationship between either DE or ME intake from the experimental diet and feed intake. Among all experiments, the crude glycerol

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(86.95% glycerol) examined in this study was found to have a DE of 3,344 ± 8 kcal/kg and a ME of 3,207 ± 10 kcal/kg when fed to growing pigs, thereby providing a highly available energy source for growing pigs.

Key words: biofuels, crude glycerol, metabolizable energy, pigs

INTRODUCTION

Crude glycerol is the principal co-product of biodiesel production (Ma and Hanna, 1999; Van Gerpen, 2005; Thompson and He, 2006), with 79 g of crude glycerol generated for every 1.0 L of biodiesel produced (Thompson and He, 2006). With current biodiesel production capacity, approximately 4.16×10^8 kg of crude glycerol could be generated annually (NBB, 2007). Multiple reviews of the metabolic effects of glycerol have been published (Lin, 1977; Tao et al., 1983; Brisson et al., 2001). Glycerol is absorbed by the gastrointestinal tract of nonruminants (Tao et al., 1983) and is utilized as an energy source (Cryer and Bartley, 1973). Glycerol is gluconeogenic with glycerol gluconeogenisis being limited by the availability of glycerol (Cryer and Bartley, 1973; Tao et al., 1983; Baba et al., 1995).

Studies examining the effects of supplementing crude glycerol to diets fed to swine (Kijora and Kupsch, 2006; Kiljora et al., 1995, 1997; Mourot et al., 1994) and broilers (Cerrate et al., 2006; Simon et al., 1996) have shown little to no effect on animal performance. Research determining the energy value of crude glycerol is limited. Recently, Bartelt and Schneider (2002) reported a decrease in the ME of glycerol as the level of dietary glycerol was increased in swine and poultry diets. In contrast, Dozier et al. (2008) in broilers and Lammers et al. (2008) in laying hens did not observe this effect. The objectives of the current study were to determine the apparent DE and ME of crude glycerol at various levels of supplementation and to determine if the apparent energy values differed between starter and finisher pigs.

MATERIALS AND METHODS

General Pig Management. The Iowa State University Animal Care and Use Committee approved all experimental protocols and all experiments utilized the same batch of crude glycerol (86.95% glycerol). The crude glycerol was characterized through standard techniques (AOAC, 1995; AOCS, 2000; ASTM 2006) and is detailed in Table 1. Crude glycerol was obtained from biodiesel production using soybean oil as the initial feedstock (AG Processing Inc., Sergeant Bluff, IA). Three experiments (Exp. 1, 3, and 4) examined crude glycerol fed to starter pigs (average initial BW, 10.3 ± 1.4 kg) whereas 2 experiments (Exp. 2 and 5) examined crude glycerol fed to finishing pigs (average initial BW, 104.7 ± 8.0 kg). In each experiment, 24 pigs were randomly assigned to individual metabolism crates equipped with screens and trays that allowed total but separate collection of feces and urine. Dimensions of individual metabolism crates were 0.53 × 0.71 m for starter pigs and 0.8 × 2.1 m for finishing pigs. Due to crate design, barrows were used in the starter pig metabolism experiments while gilts were used in the finishing pig metabolism experiments.

Pigs were randomly assigned to dietary treatments after pen assignment. Dietary treatments consisted of a common basal diet which met or exceeded NRC requirements (NRC, 1998) mixed with 0, 5, 10, or 20% crude glycerol addition to the basal diet (Exp. 1 and 2) or 0 and 10% crude glycerol addition to the basal diet (Exp. 3, 4, and 5). Basal diet formulations and calculated analyses are summarized in Table 2. A 10-d adjustment period was used to adapt pigs to the metabolism crate and the dietary treatment.

Pigs were fed 2 equal daily meals. In Exp. 1, 2, 4 and 5, pigs were fed a set amount of the basal diet with pigs on the glycerol treatments offered an increased feed allotment based on the amount of glycerol addition to the basal diet (Adeola, 2001). In Exp. 3 pigs assigned to 10% crude glycerol received 5% more feed than control pigs. In all experiments, pigs were fed twice daily with feed consumption and refusal recorded at the end of the experimental period. Table 3 details daily feed allowance and components for dietary treatments fed for each of the 5 experiments. Following the adjustment period, urine was collected for the following 5d into stainless steel buckets containing 30mL of 6 N HCl placed below the collection drain of each crate. Urine was collected twice daily, diluted with water to a constant volume, and thoroughly mixed, with a representative aliquot collected and stored at 0°C until subsequent analysis.

In Exp. 1 and 2, Fe_2O_3 (0.25% by weight) was thoroughly mixed with the initial feed allocation and fed on the evening of d 10. The appearance of the marker in the feces signaled the beginning of the fecal collection period. Feces were collected twice daily and stored at 0°C. A second pulse of Fe_2O_3 was thoroughly mixed and fed with the tenth subsequent meal (5-d collection period). Upon appearance of the second pulse of marker in the feces, collection was terminated. Because pigs seemed to have an aversion to the feed containing the marker in Exp. 1 and 2, no marker was utilized in Exp. 3, 4, and 5. Rather, total fecal collection was performed for a 120 h (5 d) time period beginning the morning of d 11 and ending the morning of d 16.

Chemical Analyses. Feed samples were ground through a 1-mm screen before energy determination. Fecal samples were thawed, dried at 70°C for 48 h, and weighed to determine the DM content. Fecal samples were ground through a 1-mm screen in preparation for energy determination. For urine energy determination, 2 mL of urine was added to 0.5 g of dried cellulose and subsequently dried at 50°C for 24 h prior to energy determination. The GE of feed, feces, and urine plus cellulose were determined using an isoperibol bomb calorimeter (model number 1281; Parr Instrument Co., Moline, IL) with benzoic acid used as a standard. Duplicate analyses were performed on all diets and samples of feces from each pig whereas triplicate analysis was performed on diluted urine plus cellulose from each pig. Urinary energy was determined by subtracting the energy contained in cellulose from the combined urine plus cellulose energy.

Calculations and Statistical Analysis. Observations from 108 pigs of the 120 pigs assigned to dietary treatments across all experiments were used for analysis. Observations from 9 pigs were not possible to quantify due to diarrhea, constipation, or feed refusal. Observations from 3 pigs exceeded their treatment group mean by more than 2 SD and were considered outliers. The authors do not have an explanation why all but 1 pig excluded from analysis received experimental diets containing crude glycerol.

Gross energy consumed was calculated by multiplying the GE value of the diet fed by feed intake over the 5-d collection period. Apparent DE values were calculated by subtracting fecal energy from intake energy. Apparent ME values were calculated by subtracting urinary energy from apparent DE. The apparent DE and ME values of crude glycerol fed to pigs were estimated as the slope of the linear relationship between the apparent DE or ME intake from the experimental diet, dependent variable, and feed intake, independent variable, (Adeola, 2001) using JMP 6.0 (SAS Institute, Inc. Cary, NC). A regression model was used to test for effect of feed intake, experiment number, fecal collection method, type of pig, and type of pig × feed intake interaction on apparent DE and ME.

RESULTS AND DISCUSSION

Production of biofuels is increasing due to rising energy prices, uncertain access to petroleum supplies, and recognition of the environmental impacts of fossil fuel use (Ma and Hanna, 1999; Hill et al., 2006; Kurki et al., 2006). Consequently, increased production of co-products from biofuels industries will necessitate livestock producers to be flexible in feedstuff choice. Crude glycerol, being a readily available energy source, may play an important role in meeting the energy needs of pigs as biodiesel production expands.

The ME of the basal diet used in the starter experiments was 3,165, 3,199, and 3,248 kcal/kg for Exp 1, 3, and 4 respectively. The ME of the basal diets used in the finisher experiments were 3,174 and 3,255 kcal/kg for Exp 2 and 5 respectively. These values are within 5% of the calculated contents for the starter and finisher basal diets and reflect good collection and analytical techniques in all experiments. The GE of crude glycerol evaluated in these experiments was determined to be 3,625 ± 26 kcal/kg. This is close to expectations relative to pure glycerol (in house GE analysis of 4,305 kcal/kg), given that our sample of crude glycerol evaluated contained 86.95% glycerol with low levels of methanol (0.028%) and free fatty acid (0.29%). Based upon our data in broilers (Dozier et al., unpublished data) and laying hens (Lammers et al., 2008) we did not expect the level of crude glycerol to affect ME determination. However, when data from Exp. 1 was analyzed separately the ME of crude glycerol declined with increasing levels of supplementation, with estimated ME values of 3,601, 3,239, and 2,579 kcal/kg crude glycerol for 5, 10, and 20% inclusion levels, respectively (quadratic, P = 0.05). Bartelt and Schneider (2002) also showed a decrease in the ME of glycerol (99.9% glycerol) with increasing levels of glycerol fed to 34-kg barrows, with ME/kg being 4,177, 3,436, and 2,524 kcal/kg at 5, 10, and 15% inclusion levels, respectively. In Exp. 1, the decrease in ME of glycerol appears to be due to pigs fed the 20% crude glycerol. Removing the 20% inclusion level data from Exp. 1 showed no such difference in ME estimation with the remaining levels of crude glycerol tested (0, 5, and 10%), resulting in a ME value of 3,463 kcal/kg (linear, P = 0.001). In contrast, there was no effect of crude glycerol inclusion level on ME determination when determined with finishing pigs in Exp. 2.

Apparent energy values for all 5 experiments are detailed in Table 4. Among all treatments, digestibility ranges between 89 and 92% while ME values are between 86 and 88% of the GE intake. The only exception is found in the starter pigs fed 20% crude glycerol (Exp. 1). The digestibility of the fed diet is 90% in those 6 pigs, however, the ME value is 83% of the GE intake. This further highlights a potential decline in the ability of 11.0-kg pigs to metabolize more than 10% crude glycerol. We do not have an explanation for this effect as enzyme kinetics involved in glycerol metabolism have not been studied in the pig and this experiment was not designed to evaluate tissue utilization or metabolism of glycerol in the pig. With 6 starter pigs fed 20% crude glycerol it is difficult to draw conclusions about the small pig's ability to utilize crude glycerol, although the question should be examined further. Given the fact that pigs fed the 20% crude glycerol in Exp. 1 had reduced utilization of crude glycerol, as determined by a lower ME estimate, we chose to exclude the pigs from subsequent analysis.

Markers such as Fe_2O_3 have long been used in nutritional studies (Kotb and Luckey, 1972). In Exp. 1 (starter) and 2 (finisher), Fe_2O_3 seemed to affect palatability of the diet through visual evaluation of feed acceptance at the initiation of the collection period. This is supported by Jagger et al. (1992) who reported that 57-kg pigs had some initial reluctance to consume feed when the level of marker was increased from 0.1% to 0.5% TiO_2. We chose not to use a marker in Exp. 3, 4, and 5 because acceptance of feed is critical in short-term metabolic studies.

Table 5 presents the apparent DE and ME values as determined by linear regression (Adeola, 2001) for Exp. 1 to 5. Apparent DE and ME were not influenced by experiment (Exp. 1 to 5), use of marker to determine fecal collection time points (Exp. 1 and 2 versus Exp. 3, 4, and 5), type of pig (starter, Exp. 1, 3, and 4 versus finisher, Exp. 2 and 5), or by type of pig × feed intake interaction. As expected, feed intake affected both apparent DE and ME intake ($P \leq 0.001$).

In the current experiments, the ratio of DE:GE for the crude glycerol examined equaled 92% indicating that crude glycerol was well digested by pigs. In comparison to corn and soybean oil, 2 common feedstuffs used to provide energy in pig diets, the ratio of ME:DE for the crude glycerol examined was 96%, which is identical to the ME:DE ratio for soybean oil and is comparable to the ratio of ME:DE for corn which is 97% (NRC, 1998). These relationships support the assertion that the crude glycerol used in these experiments was well utilized by the pig as a source of energy. This is agreement with Bartelt and Schneider (2002) who reported that > 97% of the glycerol is digested prior to the cecum.

The results of combined regressions indicate that the DE value of the examined crude glycerol (86.95%) was 3,344 ± 8 kcal/kg (Figure 1) and that the ME was 3,207 ± 10 kcal/kg (Figure 2). Recent work with the same crude glycerol sample estimated an apparent ME (corrected for nitrogen) to be 3,805 kcal/kg for laying hens (Lammers et al. 2008) and 3,684 kcal/kg for broilers (Dozier et al., 2008) which are not different from the GE for this sample of crude glycerol (3,625 ± 26 kcal/kg). Tao et al. (1983) indicated that the oxidation of glycerol to carbon dioxide releases 4,320 kcal/kg. Rosebrough et al. (1980) assumed a ME value of 4,200 kcal/kg for dietary glycerol in turkeys while Cerrate et al. (2006) estimated a ME value of 3,528 kcal/kg in broilers. Until now, no work has reported an actual determination of ME of crude glycerol in swine. When placed on an equivalent glycerol basis, our ME determination would be marginally higher than the 3,436 kcal ME/kg determined for pure glycerol (Bartelt and Schneider, 2002).

With an ME of 3,207 ± 10 kcal/kg, crude glycerol can be used as an excellent source of energy for growing pigs. Levels of other compounds in crude glycerol (i.e., methanol, sodium- or potassium chloride, and free fatty acids), however, must be monitored to prevent excessive amounts in pig diets and for potential impacts on ME determination of this feedstuff.

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Table 1. Characterization of crude glycerol

Item	Value	Analytical method
Total glycerol[1], %	86.95	ASTM[2] D 6584-00E01
Methanol[1], %	0.028	Gas chromatography (proprietary method)
pH[1]	5.33	Orion 230A pH meter with 9107 BN probe
Total fatty acid[1], %	0.29	AOCS[3] G 4.40 modified for glycerin
Moisture[4], %	9.22	AOAC[5] 984.20
Crude protein[4], %	0.41	AOAC 990.03
Crude fat[4], %	0.12	AOAC 920.39 (A)
Ash[4], %	[2]	3.19 AOAC 942.05
Sodium[4], %[2]	1.26	AOAC 956.01
Chloride[4], %[2]	1.86	AOAC 9.15.01, 943.01
Potassium[4], %[2]	< 0.005	AOAC 956.01
Color[4]	< 1	AOCS Cc 13a-43
Gross energy[6], kcal/kg	3625 ± 26	Isoperibol bomb calorimeter

[1]Values reported by AGP, Inc. Sergeant Bluff, IA, Lot # GB605-03.
[2]American Society for Testing Materials (2006)
[3]American Oil Chemists' Society (2000).
[4]Analysis by University of Missouri-Columbia Experiment Station Chemical Laboratories, Columbia, MO.
[5]Association of Official Analytical Chemists (1995).
[6]Analysis by USDA, National Swine Research and Information Center, Ames, IA; Model number 1281, Parr Instrument Co. Inc., Moline, IL.

Table 2. Ingredient and calculated content of basal diets fed to starter and finisher pigs, as-fed basis

Item	Starter[1]	Finisher[2]
Ingredient, %		
Corn	44.75	79.20
Soybean meal, 47.5%	38.92	18.30
Whey (dried)	12.50	0.00
DL-methionine	0.03	0.00
L-threonine	0.02	0.00
Dicalcium phosphate	1.84	0.90
Limestone	1.00	0.85
Sodium chloride	0.25	0.33
Trace mineral mix	0.15[3]	0.09[4]
Choline chloride, 60%	0.03	0.00
Vitamin mix	0.37[5]	0.20[6]
Mold inhibitor	0.10	0.10
Total	100.00	100.00
Calculated content		
ME, Mcal/kg	3.326	3.327
Lysine, %	1.40	0.76
Total sulfur AA, %	0.79	0.54
Threonine, %	0.96	0.57
Tryptophan, %	0.30	0.17
Calcium, %	1.02	0.60
Available phosphorus, %	0.51	0.23
Sodium, %	0.23	0.15
Chlorine, %	0.37	0.25

[1]Mean initial BW, 10.3 ± 1.4 kg.

[2]Mean initial BW, 104.7 ± 8.0 kg.

[3]Provided the following per kg of diet: Cu, 26.3 mg as Cu oxide; Fe, 263 mg as Fe sulfate; I, 3.0 as Ca iodate; Mn, 90.0 mg as Mn oxide; and Zn, 225 mg as Zn oxide.

[4]Provided the following per kg of diet: Cu, 15.8 mg as Cu oxide; Fe, 158 mg as Fe sulfate; I, 1.8 as Ca iodate; Mn, 54.0 mg as Mn oxide; and Zn, 135 mg as Zn oxide.

[5]Provided the following per kg of diet: vitamin A, 8,157 IU; vitamin D_3, 2,039 IU; vitamin E, 41 IU; vitamin B_{12}, 0.04 mg; riboflavin, 12.2 mg; niacin, 61.2 mg; d-panothentic acid, 32.6 mg.

[6]Provided the following per kg of diet: vitamin A, 4,409 IU; vitamin D_3, 1,102 IU; vitamin E, 22 IU; vitamin B_{12}, 0.02 mg; riboflavin, 6.6 mg; niacin, 33.1 mg; d-panothentic acid, 17.6 mg.

Table 3. Number of pigs, daily feed allowance[1], and components fed for 5 experiments

Experiment	Glycerol addition, %	Number of pigs	Daily intake Basal diet, g	Daily intake Glycerol, g	GE kcal/kg diet
1 (11.0 ± 0.5 kg)[2]	0	6	376	0	3,680
	5	6	376	19	3,670
	10	6	376	38	3,707
	20	6	376	75	3,681
2 (109.6 ± 5.5 kg)[2]	0	6	2,292	0	3,652
	5	6	2,292	115	3,666
	10	6	2,292	229	3,664
	20	5	2,292	458	3,690
3 (8.4 ± 0.9 kg)[3]	0	12	316	0	3,746
	10	7	300	30	3,806
4 (11.3 ± 0.7 kg)[3]	0	11	400	0	3,778
	10	9	400	40	3,780
5 (99.9 ± 7,4 kg)[3]	0	12	2,000	0	3,783
	10	10	2,000	200	3,768

[1]Pigs were fed 2 equal meals daily in each experiment.
[2]Fecal collection by marker method.
[3]Fecal collection by 120 h method.

Table 4. Apparent energy values for 5 experiments[1]

Item	Glycerol Addition, % 0	5	10	20
Experiment 1 initial BW, 11.0 ± 0.5 kg				
Gross energy intake, kcal/d	1,384 ± 13	1,450 ± 16	1,535 ± 1	1,660 ± 5
Fecal energy, kcal/d	147 ± 19	138 ± 14	146 ± 21	168 ± 19
Digestible energy, kcal/d	1,237 ± 19	1,311 ± 14	1,389 ± 21	1,491 ± 19
Urinary energy, kcal/d	47 ± 16	56 ± 19	68 ± 25	108 ± 25
Metabolizable energy, kcal/d	1,190 ± 30	1,255 ± 25	1321 ± 36	1,384 ± 29
Experiment 2 initial BW, 109.6 ± 5.5 kg				
Gross energy intake, kcal/d	8,370 ± 46	8,824 ± 8	9,237 ± 64	10,148 ± 89
Fecal energy, kcal/d	798 ± 108	811 ± 48	885 ± 83	828 ± 50
Digestible energy, kcal/d	7,573 ± 108	8,013 ± 48	8,352 ± 83	9,320 ± 50
Urinary energy, kcal/d	298 ± 28	282 ± 24	350 ± 40	600 ± 44
Metabolizable energy, kcal/d	7,277 ± 124	7,731 ± 53	8,002 ± 81	8,720 ± 83
Experiment 3 initial BW, 8.4 ± 0.9 kg				
Gross energy intake, kcal/d	1,180 ± 1		1,256 ± 1	
Fecal energy, kcal/d	121 ± 14		115 ± 9	
Digestible energy, kcal/d	1,059 ± 14		1,141 ± 9	
Urinary energy, kcal/d	48 ± 8		61 ± 19	
Metabolizable energy, kcal/d	1,011 ± 18		1,080 ± 23	
Experiment 4 initial BW, 11.4 ± 0.7 kg				
Gross energy intake, kcal/d	1,511 ± 2		1,663 ± 10	
Fecal energy, kcal/d	160 ± 21		150 ± 16	
Digestible energy, kcal/d	1,352 ± 21		1,514 ± 16	
Urinary energy, kcal/d	53 ± 7		73 ± 12	
Metabolizable energy, kcal/d	1,299 ± 23		1,441 ± 18	
Experiment 5 initial BW, 99.9 ± 7.4 kg				
Gross energy intake, kcal/d	7,566 ± 27		8,290 ± 33	
Fecal energy, kcal/d	858 ± 136		836 ± 86	
Digestible energy, kcal/d	6,708 ± 136		7,451 ± 86	
Urinary energy, kcal/d	198 ± 38		264 ± 31	
Metabolizable energy, kcal/d	6,510 ± 158		7,187 ± 90	

[1]Calculated energy values presented as Mean ± SEM.

Table 5. Apparent energy value of crude glycerol fed to pigs, as-fed basis[1]

Experiment	Pigs	Initial BW, kg	DE, kcal/kg	SEM	ME, kcal/kg	SEM
1	18	11.0 ± 0.6	4,401	282	3,463	480
2	23	109.6 ± 5.5	3,772	108	3,088	118
3	19	8.4 ± 0.9	3,634	218	3,177	251
4	20	11.3 ± 0.7	4,040	222	3,544	237
5	22	99.9 ± 7.4	3,553	172	3,352	192

[1]All experiments represent data from 5-d energy balance experiments following a 10-d adaptation period.

Figure 1

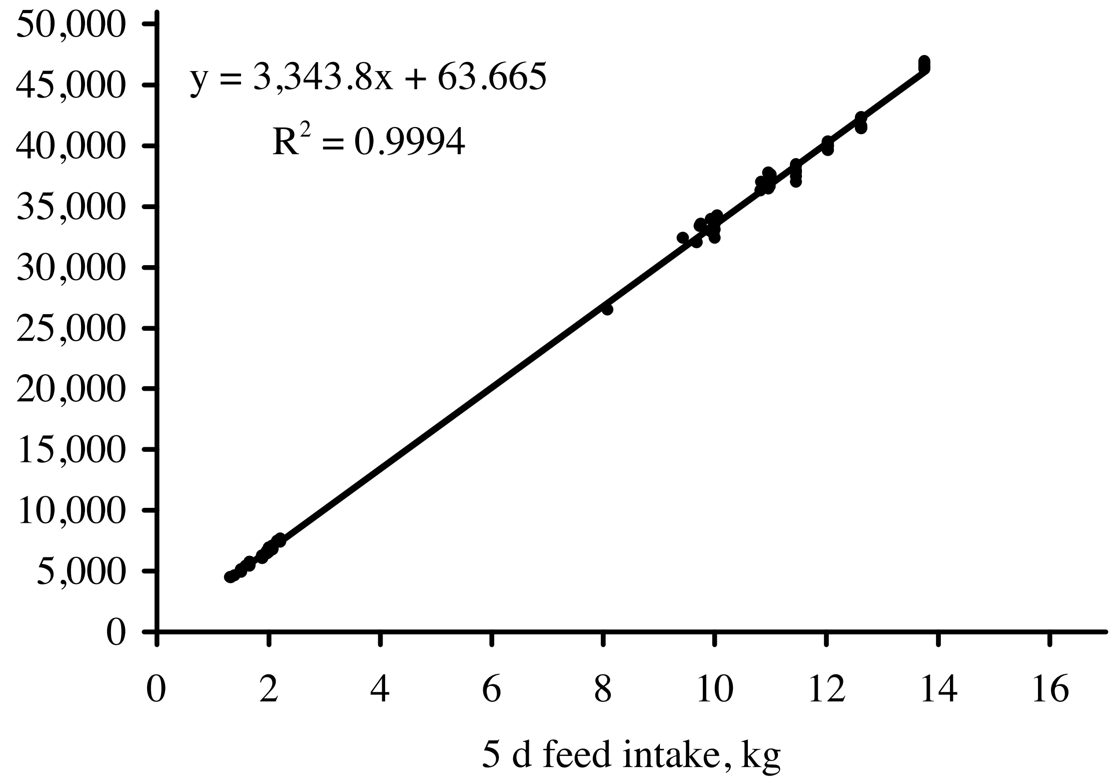

Figure 1. Apparent DE of crude glycerol fed to pigs. Data represents the combined regression from Exp. 1 through 5 of DE intake over feed consumption for a 5-d period for 102 pigs fed 0, 5, 10, and 20% crude glycerol, with the slope of the regression line indicating crude glycerol's DE equals 3,344 kcal/kg.

Figure 2

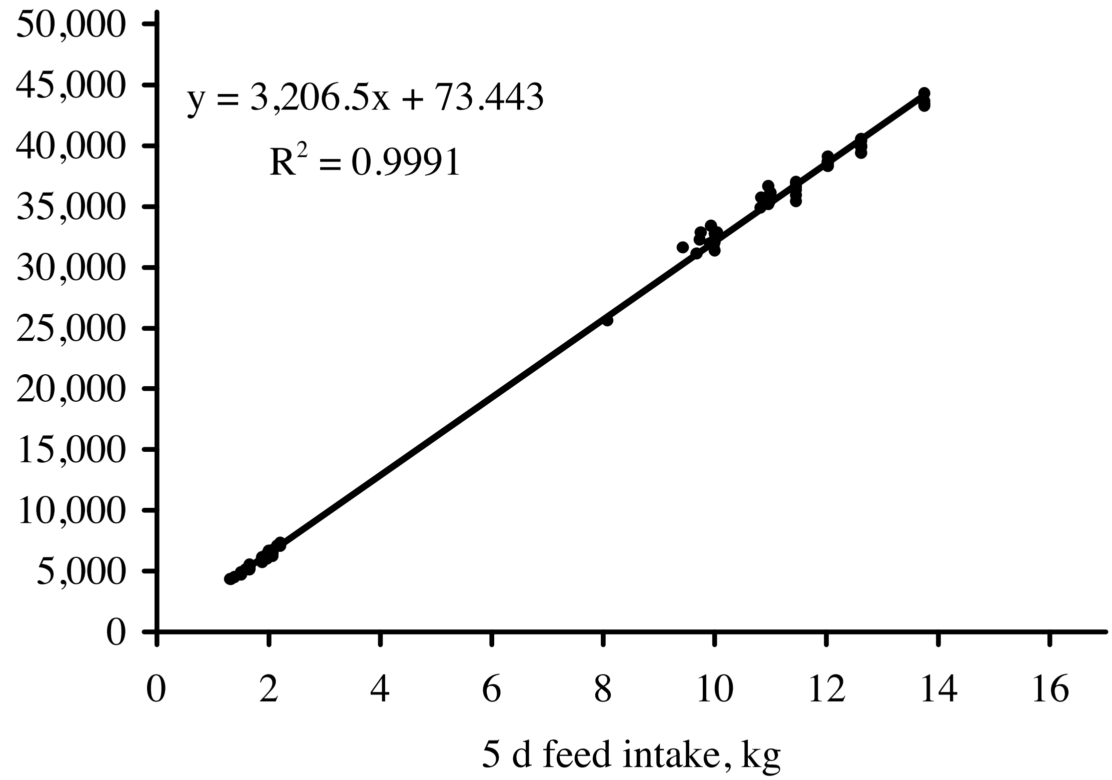

Figure 2. Apparent ME of crude glycerol fed to pigs. Data represents the combined regression from Exp. 1 through 5 of ME intake over feed consumption for a 5-d period for 102 pigs fed 0, 5, 10, and 20% crude glycerol, with the slope of the regression line indicating crude glycerol's ME, equals 3,207 kcal/kg.

CHAPTER 6. GROWTH PERFORMANCE, CARCASS CHARACTERISTICS, MEAT QUALITY, AND TISSUE HISTOLOGY OF GROWING PIGS FED CRUDE GLYCERIN-SUPPLEMENTED DIETS

A paper published in the *Journal of Animal Science*[4]

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ABSTRACT: The effects of dietary crude glycerin on growth performance, carcass characteristics, meat quality indices, and tissue histology of growing pigs fed crude glycerin were determined in a 138-d feeding trial. Crude glycerin utilized in the trial contained 84.51% glycerin, 11.95% water, 2.91% sodium chloride, and 0.32% methanol. Eight days post-weaning, 96 pigs (48 barrows, 48 gilts, average BW of 7.9 ± 0.4 kg) were allotted to 24 pens (4 pigs/pen), with sex and BW balanced at the start of the experiment. Dietary treatments were 0, 5, and 10% crude glycerin inclusion into corn-soybean meal based diets and were randomly assigned to pens. Diets were offered ad libitum in meal form and formulated to be equal in ME, sodium, chloride, and Lys, with other AA balanced on an ideal AA basis. Pigs and feeders were weighed every other week to determine ADG, ADFI, and G:F. At the end of the trial, all pigs were scanned using real time ultrasound and subsequently processed at a commercial abattoir. Blood samples were collected pretransport and at the time of harvest for plasma metabolite analysis. In addition, kidney, liver, and eye

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tissues were collected for subsequent examination for lesions characteristic of methanol toxicity. After an overnight chilling of the carcass, loins were removed for meat quality, sensory evaluation, and fatty acid profile analysis. Pig growth, feed intake, and G:F were not affected by dietary treatment. Dietary treatment did not affect 10^{th}-rib backfat, LM area, percent fat free lean, meat quality, or sensory evaluation. Loin ultimate pH was increased (P= 0.06) in pigs fed the 5 and 10% crude glycerin compared with pigs fed no crude glycerin (5.65 and 5.65 versus 5.57 respectively). Fatty acid profile of the LM was slightly changed by diet with the LM from pigs fed 10% crude glycerin having less linoleic acid ($P < 0.01$) and more eicosapentaenoic acid ($P = 0.02$) than pigs fed the 0 or 5% crude glycerin diets. Dietary treatment did not affect blood metabolites or frequency of lesions in the examined tissues. This experiment demonstrated that pigs can be fed up to 10% crude glycerin with little to no effect on pig performance, carcass composition, meat quality, or lesion scores.

Key words: biofuels, crude glycerin, fatty acids, growing pigs, histology, meat quality

INTRODUCTION

The production of biofuels fuels is increasing in a dramatic fashion (Ma and Hanna, 1999; Hill et al., 2006; Kurki et al., 2006). Biodiesel production in the United States have grown exponentially since 1999 with existing U.S. production capacity being approximately 5.3 billion L (National Biodiesel Board 2007). A co-product of the biodiesel industry is crude glycerin, with 79 g of crude glycerin generated for every 1.0 L of biodiesel produced (Thompson and He, 2006). Consequently, with current biodiesel production capacity, approximately 4.2×10^8 kg of crude glycerol could be generated annually (National Biodiesel Board 2007).

Crude glycerin obtained from a biodiesel production facility using soybean oil as its feedstock has been shown to be a highly available energy source in laying hens (Lammers et al., 2008a), broilers (Dozier III et al., 2008), and swine (Lammers et al., 2008b). Pigs can be fed up to 10% glycerin with little or no effect on pig performance (Kiljora et al., 1995, 1997) . The reported effect of glycerin on meat quality has been inconsistent. In pigs fed wheat–soybean meal based diets, 24-h drip loss and cooking loss were reduced in the muscles from pigs supplemented with 5% crude glycerin (Mourot et al., 1994). In contrast, Kijora and Kupsch (2006) noted no effect on carcass dripping or press water loss in barley–soybean meal based diets supplemented with up to 10% glycerin. Crude glycerin supplementation has been shown to slightly increase oleic acid at the expense of linoleic and linolenic acids, consequently decreasing the unsaturation index of fat (Mourot et al., 1994; Kijora et al., 1997).

Low concentrations of methanol are contained in crude glycerin and acute methanol intoxication can lead to formic acid accumulation leading to metabolic acidosis (Medinsky and Dorman, 1995; Skrzydlewska, 2003). Animals differ widely, however, in their ability to metabolize methanol (Roe 1982). Although crude glycerin contains trace concentrations of methanol, no data exist on the effect of crude glycerin containing methanol on tissue histology in growing pigs. The objectives of the current study were to evaluate effects of crude glycerin supplementation on growing-finishing pig performance, carcass composition, meat quality, composition and profile of LM intramuscular lipid, and histology of the eye, liver, and kidney tissue.

MATERIALS AND METHODS

The Iowa State University Animal Care and Use Committee approved all experimental protocols.

Animals and Dietary Treatments. Crude glycerin was obtained from a biodiesel production facility (AG Processing Inc., Sergeant Bluff, IA) that utilized soybean oil as its feedstock. The analysis of the crude glycerin used in this study is listed in Table 1.

Pigs (Cambrough 22 females × L337 sires) were weaned at 21 d of age and fed a commercial starter diet for 1 wk. Eight days post-weaning, 96 pigs (48 gilts, 48 barrows) with an average BW of 7.9 ± 0.4 kg were allotted to 24 pens (4 pigs/pen) with sex distribution and pen weight balanced at the start of the experiment. Dietary regimes were randomly assigned to each pen, with dietary treatments being 0, 5, and 10% crude glycerin inclusion into corn-soybean meal diets. Pigs were fed diets over a 5-phase feeding program during the 138-d trial. Within each phase, diets were offered ad libitum in meal form and were formulated to be equal in ME, sodium, chloride, with diets based on total Lys with other AA balanced on an ideal AA basis. Initial diet formulation and calculated nutrient content of control diets are summarized in Table 2.

Pigs were individually weighed every 2 wk with feed disappearance recorded at the time of pig weighing to determine ADG, ADFI, and G:F. Dietary phase changes corresponded with the day that pigs were weighed, occurring on the same day for all treatments. Pigs were housed in nursery (1.2 × 1.2 m) pens for 33 d, grower (1.8 × 1.9 m) pens for 28 d, and finisher (2.7 × 1.8 m) pens for the final 77 d. Nursery pens had wire mesh flooring while the grower and finisher pens had partial slats. All rooms were mechanically ventilated with pull-plug manure storage systems. During the course of the experiment 6 pigs were removed from the trial due to health issues with no pattern of pig removal based on dietary treatment and no individual pen having more than 1 pig removed. Pen feed disappearance was adjusted for the removed pig at the time of removal. On d-138, all pigs were weighed (133 ± 6 kg BW) for the termination of the performance period and scanned using real-time ultrasound as described by Sullivan et al. (2007) Blood samples (10 mL) for plasma analysis were collected via jugular venipuncture into containers containing sodium heparin and stored on ice until blood collection from all pigs was complete. Samples were then centrifuged at 900 × g for 20 min at 4°C, after which an aliquot of plasma from each sample was used for plasma urea nitrogen analysis. Pigs remained in their respective pens with access to feed and water until transport to the abattoir on d-139.

Carcass Traits. On the morning of d-139, 90 pigs were transported to the abattoir (Sioux-Preme Packing Co., Sioux Center, IA). One pig died during transport. On d-140, pigs were electrically stunned and exsanguinated. Blood, eye, and liver samples were harvested from early post-mortem carcasses for further analysis. Carcasses were chilled overnight (0°C). Last rib fat depth was measured on each carcass at 24 h postmortem and the percent lean was calculated (proprietary equation, Sioux-Preme Packing Co.). The loin from the left side of each carcass (10^{th} rib to posterior tip) was removed, vacuum packaged, placed on ice, transported to Iowa State University, and stored at 0°C until subsequent analysis. Tissue and loin samples from 2 pigs were not collected at the abattoir due to operator error. Loin marbling scores were evaluated 12 d postmortem according to National Pork Board Standards (NPPC, 2000). Loin muscle was evaluated for moisture composition(AOAC, 1990) with loin purge determined on additional loin samples after 12 d of storage as described by Gardner (2006) Following loin purge loss, chop purge was determined using

2.54 cm-thick chops which were weighed and placed in a plastic bag and stored for 24 h at 2.2±1.1°C with chop purge based on the weight of free liquid in the bag (Garderner et al. 2006). Drip loss was determined using 2.54-cm thick boneless chops (2 per loin) as detailed by Lonergan et al. (2001). Minolta color values from each chop were obtained with a Minolta Chroma meter (model CR-310; Knoica Minolta Sensing Americas Inc., Ramsey NY) with a 0° viewing angle, a 50-mm diameter measuring area, and a CIE D_{65} illuminant. One measurement was taken on each chop sample.

Cooked Loin Evaluation. The loins of 2 pigs from each pen (1 barrow and 1 gilt) were randomly selected for evaluation. Following 12 d of storage, two 2.54-cm-thick loin chops were removed from the center of the loin for sensory and instrumental texture analysis as described by Sullivan et al. (2007).

Fatty Acid Profile Analysis. Lipids were extracted and measured from a sample of each loin (Folch et al., 1957), which were subsequently methylated to fatty acid methyl esters using boron trifluride (BF_3) in methanol, and removed from solution as described by Du et al. (1999). The fatty acid methyl esters were analyzed for fatty acid composition according to procedures established by Du et al. (1999) using gas chromatography (HP 6890 equipped with an autosampler, flame ionization detector, Agilent Technologies, Santa Clara, CA) and a column (HP-wax fused silica capillary column, 30 m × 0.25 mm × 0.25 μm film thickness; Supelco, Bellefonte, PA). Fatty acid methyl esters were identified by comparing the retention times of authentic fatty acid standards.

Plasma Metabolites. In addition to obtaining blood samples from all pigs before shipping, blood samples were also collected on the day of slaughter at the time of exsanguination into 50-mL cetrifuge tubes containing sodium heparin (14.2 USP units/mL).

Samples were subsequently centrifuged at 900 × g for 20 min and stored at -80°C pending analysis. Blood urea nitrogen was determined enzymatically as described previously (Kerr et al., 2004). Plasma cortisol was determined using a commercially available kit (Active Cortisol EIA, Diagnostic Systems Laboratories, Inc., Webster, TX) that has been previously validated for porcine serum (Weber and Spurlock, 2004). Commercially available kits (Sigma Chemical Co. St. Louis, MO) were used to measure plasma glucose and glycerol (GAHK20 and F6428 respectively). In addition, commercially available kits (Pointe Scientific Inc., Canton MD) were used to measure plasma lactate concentrations and creatine kinase activity (L7596 and C7512, respectively). All of the plasma metabolites were measured in duplicate.

Tissue Histology. From all pigs, 1 eye, liver, and kidney per pig were collected at the time of slaughter and placed in neutral-buffered 10% formalin. They were subsequently processed by routine paraffin embedding techniques, cut in 4 µm sections, and stained with hematoxylin and eosin and Masson's trichrome techniques. All sections were read for lesions (Maxie, 2007) twice by a single person versed in lesion evaluation.

Statistical Analysis. Data were subjected to ANOVA (SAS Inst. Inc., Cary, NC) and differences between means were tested using the PDIFF option. Pig performance (ADG, ADFI, and G:F) was evaluated in each dietary phase and for the entire 138-d feeding period with the pen used as the experimental unit. Carcass composition and meat quality traits were evaluated to test for effect of dietary treatment, pig gender, and diet × gender interaction. Plasma metabolites pre-transport and immediately post-exsanguination, and differences in the frequency of histological lesions were evaluated for the effect of dietary treatment.

Individual pigs were the experimental unit for analysis of carcass composition, meat quality, plasma metabolites and lesion data.

RESULTS AND DISCUSSION

Average daily gain, ADFI, and G:F were not affected by dietary treatment in any phase (data not shown) or over the entire growing 138 d period (Table 3). These results agree with results from previous studies examining growth and performance of pigs fed crude glycerol in barley-soybean meal (Kiljora et al., 1995; Kijora et al., 1997; Kijora and Kupsch, 2006) and wheat-soybean meal diets (Mourot et al., 1994). This is also supported by work in broilers that demonstrated up to 5% glycerin can be fed without affecting growth or feed conversion (Simon et al., 1996; Cerrate et al., 2006).

The effects of diet, gender, and their potential interaction on carcass characteristics are described in Table 4. There was no diet × gender interaction on any trait examined. In agreement with other reports (Mourot et al., 1994; Kiljora et al., 1995; Kijora et al., 1997; Kijora and Kupsch, 2006) dietary treatment did not effect 10^{th} rib backfat, LM area, fat free lean, daily lean gain, or carcass lean percentage. As expected 10^{th} rib backfat was thicker in barrows than gilts (Cline and Richert, 2001; Renaudeau and Mourot, 2007).

Diet did not affect HCW, percent loin lean, moisture content, or chop lipid percentage (Table 5). These results agree with other reports (Mourot et al., 1994; Kiljora et al., 1995, 1997; Kijora and Kupsch, 2006). Inclusion of glycerin in the diet did not affect chop drip loss, with is in agreement with Kijora and Kupsch (2006) and Airhart et al. (2002) but contrary to the findings of Mourot et. al (1994). As expected, carcasses from gilts weighed less and were leaner than the carcasses from barrows ($P \leq 0.05$).

Loin tissue from pigs fed 10 % crude glycerin had less concentrations of linoleic acid (18:2) than the other dietary treatments ($P < 0.01$; Table 5) which agrees with the work of Morout et al. (1994) and Kijora et al. (1997). Eicosapentaenoic acid (20:5) increased with increasing crude glycerin supplementation ($P = 0.02$). Morout et al. (1994) did not report eicosapentoic acid (20:5) concentrations but reported declines in myristic acid (14:0) in backfat and linolenic acid (18:2) in backfat and semimembranosus muscle when pigs were fed 5% glycerin. Kijora et al. (1997) did not find these changes in backfat from pigs fed 10% glycerin. There is no clear consensus on the effect feeding crude glycerin may have on fatty acid profile of pork lipid (Mourot et al., 1994; Kijora et al., 1997). The apparent disagreement on the effect feeding glycerin has on fatty acid profile of pork fat may be due to differences in amount and profile of fatty acids remaining in the crude glycerin, or in our case, the reduction in corn (and consequently corn oil) due to the addition of crude glycerin. The relative differences in amount and profile of fatty acids in other feedstuffs included in the experimental diets may also limit comparisons across studies.

Dietary glycerin may reduce water loss from the carcass and cooking if slaughter follows and overnight fast (Mourot et al., 1994). In the current experiment however, pork loin quality and sensory characteristics were not affected by diet or sex and there was no diet × sex interaction (Table 6) Furthermore, data presented here indicate that cooking loss is not affected by crude glycerin supplementation, which is in contrast with the findings of Mourot et al. (1994) who reported less carcass drip loss and cooking loss from muscle of pigs fed 5% glycerin. The lack of a change in drip and cooking loss in the current study may be due to the 30-h feed withdrawal time compared with the overnight fast in the study by Mourot et al. (1994). Other workers have demonstrated that removing feed 24 h before slaughter will reduce drip loss and lessens decline in muscle pH (Jones et al., 1985; Eikenlenboom et al., 1990). Eikenlenboom et al. (1990) also reported reduced cooking loss in pigs fasted 24 h before slaughter. This is the first report of sensory evaluation of loin chops from pigs fed crude glycerol. Diet did not impact pork quality traits evaluated by a trained sensory panel.

There was no diet × time interaction or diet effect on any plasma metabolite measured (Table 7). Plasma urea nitrogen is an indicator of body protein status (Kohn et al., 2005) and has been used to determine protein requirements and lean tissue growth rates in pigs (Chen et al., 1995; Coma et al., 1995). Plasma urea nitrogen was not affected by time of collection or diet, supporting the conclusion that lean tissue mobilization was not altered by feeding up to 10% crude glycerin. Glycerin is absorbed by the gastrointestinal tract of nonruminants (Tao et al., 1983) and crude glycerin has been shown to be a source of energy in both pigs (Lammers et al. 2008b) and chickens (Dozier et al. 2008; Lammers et al. 2008a). The absence of a dietary treatment effect on plasma glycerol concentrations indicates metabolism of dietary glycerin was not affected at levels less than or equal to 10% of the diet. Concentrations of most plasma metabolites were different between pre-transport and at the time of slaughter ($P < 0.01$). Transporting pigs has been shown to cause stress in pigs (Pérez et al., 2002; Apple et al., 2005). Increases in plasma cortisol, glucose, lactate, and creatine phosphokinase are correlated with increased stress in pigs (Brown et al., 1998; Pérez et al., 2002; Apple et al., 2005). Our results indicate a stress response in pigs were following transport to the abattoir and that feeding crude glycerol did not reduce this effect.

Current biodiesel processing techniques utilize methanol which is not completely recovered, and thus, methanol is found in crude glycerol at very low concentrations (Table 1). Intermediates in the metabolism of methanol to carbon dioxide and water are formaldehyde and formate. The toxic effects of methanol poisoning are actually due to the formation, accumulation, and slow metabolism of formate in some species (Medinsky and Dorman, 1995; Skrzydlewska, 2003). Clinical consequences of methanol poisoning are central nervous system depression, vomiting, severe metabolic acidosis, blindness, and Parkinsonian-like motor disease (Roe, 1982; Dorman et al., 1993; Skrzydlewska, 2003). During the course of this study, no pig demonstrated any clinical symptoms of methanol toxicity. The 6 animals that were removed during the trial were removed for respiratory disease or lameness, with no attribution to a specific dietary treatment. Of the 89 pigs harvested, no gross lesions were observed at the time of collection. In addition, the frequency of histological lesions in kidney, liver, and eye, the pharmacological targets for methanol toxicity, were not influenced by dietary treatment (Table 8). This agrees with an earlier study in which no pathological changes in liver or kidney in response to consumption of crude glycerin during finishing (Kiljora et al., 1995).

Provided diets are formulated on an equal energy basis, the results from this study demonstrate that up to 10% crude glycerin can be fed to growing-finishing pigs with little to no effect on pig performance, carcass composition, meat quality, or lesion scores in the eye, liver, or kidney tissue. Although we noted only small effects on ultimate pH and fatty acid profiles of the LM, the decline in drip and cooking losses as reported by Mourot et al. (1994) may warrant further examination of crude glycerin supplementation on meat quality through evaluation of the amount, method, or length of administration. Combined with our previous work evaluating the energy value of crude glycerin in nonruminants (Lammers et al., 2007; Dozier III et al., 2008; Lammers et al., 2008), we conclude that crude glycerin is a viable source of dietary energy that is well utilized by pigs. Lastly, although this study was not designed to specifically examine the toxicology of methanol fed to pigs, the results indicate that the levels of methanol in these diets did not negatively affect pig performance or frequency of histological lesions in tissues assocated with methanol metabolism.

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Table 1. Characterization of crude glycerin

Item	Value	Analytical method
Total glycerin[1], %	84.51	Determined by difference[2]
Methanol[1], %	0.32	Gas chromatography (proprietary method)
pH[1]	5.67	Orion 230A pH meter with 9107 BN probe
Total fatty acid[1], %	0.00	AOCS[3] G 4.40 modified for glycerin
Moisture,[4] %	11.95	AOAC[5] 984.20
Crude protein,[4] %	0.82	AOAC 990.03
Crude fat,[4] %	0.23	AOAC 920.39 (A)
Ash,[4] %[2]	2.98	AOAC 942.05
Sodium,[4] %[2]	1.20	AOAC 956.01
Chloride,[4] %[2]	1.71	AOAC 9.15.01, 943.01
Potassium,[4] %[2]	< 0.005	AOAC 956.01
Color[4]	< 1	AOCS Cc 13a-43
Metabolizable energy,[6] kcal/kg	3,638	Predicted value[3]

[1]Values reported by AGP, Inc. Sergeant Bluff, IA, Lot # GB608-25.

[2]Determined within the AGP Inc. laboratory as: 100 - % methanol - % total fatty acid - % moisture - % NaCl.

[3]AOCS (2000).

[4]Analysis by University of Missouri-Columbia Experiment Station Chemical Laboratories, Columbia, MO.

[5]AOAC (1995).

[6]ME of crude glycerin = GE of pure glycerin × purity of crude glycerin = 4,305 kcal/kg × 84.51%. Based on Lammers et al. (2007).

Table 2. Initial diet formulation and calculated nutrient content of control experimental diets fed to pigs[1]

Phase	I	II	III	IV	V
Weight range, kg	7–12	12–23	23–45	45–78	78–120
Ingredient, %					
Corn	54.00	64.50	69.50	77.30	84.40
Soybean meal	30.90	30.90	26.50	20.00	13.50
Soybean oil	1.00	0.65	0.65	0	0
Dried whey	10.00	0	0	0	0
L-lysine·HCl	0.27	0.17	0.15	0.10	0.09
DL-methionine	0.09	0.06	0	0	0
L-threonine	0.09	0.07	0.03	0	0
Dicalcium phosphate	2.12	2.05	1.42	1.10	0.76
Ground limestone	0.73	0.70	1.00	0.77	0.55
Sodium chloride	0.26	0.40	0.35	0.33	0.30
Choline chloride, 60%	0.03	0	0	0	0
Vitamin premix[2,3]	0.35	0.35	0.25	0.25	0.25
Mineral premix[4,]	0.16	0.15	0.15	0.15	0.15
Total	100.00	100.00	100.00	100.00	100.00
Calculated analysis					
ME kcal/kg	3,294	3,305	3,327	3,321	3,343
Lysine, %	1.37	1.23	1.10	0.88	0.70
Total sulfur AA, %	0.76	0.73	0.61	0.53	0.47
Threonine, %	0.89	0.83	0.72	0.58	0.49
Tryptophan, %	0.25	0.23	0.21	0.18	0.14
Calcium, %	0.97	0.88	0.75	0.96	0.79
Available phosphorus, %	0.54	0.46	0.34	0.27	0.20
Sodium, %	0.21	0.18	0.16	0.15	0.14
Chlorine, %	0.35	0.29	0.27	0.25	0.24

[1]Dietary treatments 5 and 10 consisted of the above diets formulated to include 5 or 10% crude glycerin respectively while remaining constant in terms of calculated ME, listed amino acid content, available phosphorus, sodium, and chlorine. Crude glycerin replaced 7 to 10% corn and 40 to 60% sodium chloride at 5% level and 15 to 17% corn and 80 to 100% sodium chloride at 10% level.

[2]Provided the following per kilogram in phase I and II diets: vitamin A, 7,718 IU; vitamin E, 40 IU; niacin, 57 mg; D-panothenic acid, 31 mg; riboflavin, 12 mg.

[3]Provided the following per kilogram in phase III through V diets: vitamin A, 5,513 IU; vitamin E, 29 IU; niacin, 42 mg; D-panothenic acid, 22 mg; riboflavin, 8 mg.

[4]Provided the following per kilogram in phase I diet: Zn, 156 mg as ZnO; Fe, 280 mg as Fe_2SO_4; Cu, 1.4 mg as CuO; Mn, 73 mg as MnO_2; I, 3.2 mg as CaI.

[5]Provided the following per kilogram of phase II through V diets: Zn, 146 mg as ZnO; Fe, 263 mg as Fe_2SO_4; Cu, 1.3 mg as CuO; Mn, 68 mg as MnO_2; I, 3.0 mg as CaI.

Table 3. Growth and performance of growing pigs fed crude glycerin[1]

	Diet[2]				
	0	5	10	SEM	*P*-value
Replicates, pen[3]	8	8	8		
Start weight, kg	7.9	8.0	7.8	0.2	0.60
End weight, kg	132.9	134.0	132.8	2.3	0.92
ADG, g/d	905	913	906	16	0.93
ADFI, g/d	2,333	2,385	2,400	52	0.66
G:F	0.39	0.38	0.38	0.01	0.12

[1]138-d feeding trial.

[2]Dietary treatments were 0, 5, or 10% crude glycerol inclusion in corn-soybean meal diets fed in 5 phases.

[3]4 pigs were initially assigned to each pen, over the course of the experiment 6 pigs were removed with no pen having more than 1 pig removed.

Table 4. Effect of crude glycerin on estimated carcass characteristics[1]

	Diet[2]				Gender			*P*-value		
	0	5	10	SEM	Barrow	Gilt	SEM	Diet	Gender	D × G
Pigs, number	30	29	31		44	46				
Initial BW, kg	8.0	8.0	7.9	0.2	7.9	8.0	0.2	0.80	0.78	0.69
Final BW, kg	133	134	133	2.0	137	129	2.0	0.93	0.01	0.92
10th rib backfat, mm	18.8	21.0	20.7	0.8	22.0	18.3	0.7	0.14	0.01	0.13
LM area, cm^2	48.6	49.0	46.6	0.9	48.0	48.1	0.7	0.12	0.92	0.33
Fat free lean, %	52.0	51.8	50.6	0.8	51.9	51.1	0.6	0.37	0.34	0.78
Lean gain, g/d	365	363	355	5.0	364	358	4.0	0.37	0.30	0.70

[1]From ultrasound scan data.

[2]Dietary treatments were 0, 5, or 10% crude glycerin inclusion in corn-soybean meal diets fed in 5 phases over a 138-d feeding trial.

Table 5. Carcass characteristics and fatty acid profile of loin chops from pigs fed crude glycerin

	Diet[1]				Gender			*P*-value		
	0	5	10	SEM	Barrow	Gilt	SEM	Diet	Gender	D × G
Loins, number	27	29	31		43	44				
Hot carcass wt, kg	95.2	97.2	97.3	1.8	98.7	94.5	1.4	0.61	0.03	0.97
Lean, %	55.8	54.7	55.5	0.5	54.7	56.0	0.4	0.21	0.02	0.61
Moisture, %	74.0	73.9	74.0	0.1	73.8	74.1	0.1	0.78	0.01	0.78
Total lipid, %	1.30	1.31	1.25	0.03	1.30	1.27	0.02	0.31	0.30	0.47
Ultimate pH	5.57	5.65	5.65	0.03	5.63	5.62	0.02	0.06	0.77	0.59
Drip loss, %	0.85	0.73	0.81	0.10	0.79	0.80	0.08	0.67	0.96	0.87
Loin purge, %	1.67	1.84	1.62	0.17	1.77	1.65	0.13	0.61	0.54	0.43
Chop purge, %	3.72	3.84	3.90	0.30	3.70	3.94	0.20	0.90	0.46	0.24
Chop lipid, %	2.15	2.07	2.08	0.07	2.19	2.02	0.06	0.71	0.04	0.70
Fatty acids[2]										
14:0	1.29	1.31	1.25	0.03	1.30	1.27	0.02	0.06	0.03	0.04
16:0	24.10	24.14	24.15	0.19	24.29	23.97	0.16	0.98	0.15	0.48
16:1 (*n* – 7)	3.73	3.87	3.82	0.08	3.79	3.83	0.07	0.45	0.65	0.29
17:0	0.28	0.29	0.25	0.02	0.28	0.27	0.01	0.28	0.64	0.68
17:1 (*n* – 10)	0.27	0.30	0.30	0.01	0.29	0.29	0.01	0.08	0.68	0.59
18:0	11.68	11.77	12.00	0.18	11.86	11.78	0.14	0.41	0.69	0.39
18:1	39.47	38.92	40.18	0.44	39.90	39.14	0.36	0.12	0.13	0.75
Unknown	5.12	5.24	5.10	0.10	5.08	5.22	0.08	0.57	0.26	0.23
18:2 (*n* – 6)	10.34	10.34	9.27	0.26	9.68	10.28	0.21	0.01	0.04	0.63
18:3 (*n* – 3)	0.27	0.29	0.27	0.02	0.26	0.30	0.02	0.78	0.17	0.65
20:0	0.13	0.13	0.13	0.01	0.13	0.13	0.01	0.55	0.82	0.75
20:4 (*n* –6)	2.96	3.00	2.90	0.10	2.78	3.13	0.08	0.76	0.01	0.76
20:5 (*n* – 3)	0.09	0.10	0.11	0.01	0.09	0.10	0.01	0.02	0.05	0.90
22:5 (*n* – 6)	0.28	0.29	0.28	0.01	0.26	0.30	0.01	0.08	0.01	0.75

[1]Dietary treatments were 0, 5, or 10% crude glycerin inclusion in corn-soybean meal diets fed in 5 phases over a 138-d feeding trial.

[2]Fatty acids are expressed as g/100g total fatty acids. Fatty acids are designated by the number of carbon atoms followed by the number of double bonds. The position of the first double bond relative to the methyl (*n*) end of the molecule is also included.

Table 6. Meat quality and sensory evaluation of loin chops from pigs fed crude glycerin

	Diet[1]				Gender			*P*-value		
	0	5	10	SEM	Barrow	Gilt	SEM	Diet	Gender	D × G
Loins, number	16	16	16		24	24				
Loin marbling score[2]	2.0	2.1	2.1	0.1	2.1	2.0	0.1	0.81	0.60	0.61
Cook loss, %	18.3	17.9	18.6	0.9	18.7	17.9	0.7	0.86	0.45	0.79
Japanese color score[3]	2.6	2.7	2.8	0.8	2.7	2.7	0.1	0.79	0.83	0.51
Hunter L*[4]	53.4	53.0	53.4	0.9	53.7	52.9	0.8	0.95	0.48	0.42
Minolta L*[4]	55.6	55.3	55.6	0.8	55.8	55.1	0.7	0.95	0.48	0.42
Minolta a*[4]	17.5	17.4	17.4	0.2	17.3	17.6	0.1	0.88	0.23	0.09
Minolta b*[4]	4.9	5.1	4.6	0.4	4.9	4.9	0.3	0.68	0.94	0.12
Instron, kg force[5]	6.0	5.9	6.0	0.3	6.2	5.7	0.2	0.91	0.10	0.14
Juiciness score[6]	5.5	5.7	5.5	0.4	5.4	5.7	0.3	0.93	0.54	0.35
Tenderness score[6]	6.1	6.1	5.9	0.4	5.8	6.3	0.3	0.93	0.24	0.29
Chewiness score[6]	3.6	3.4	3.3	0.3	3.5	3.3	0.2	0.74	0.39	0.31
Pork flavor score[6]	2.2	2.2	2.2	0.1	2.2	2.2	0.1	0.91	0.56	0.05
Off-flavor score[6]	3.5	3.4	3.1	0.3	3.2	3.5	0.3	0.68	0.35	0.23

[1]Dietary treatments were 0, 5, or 10% crude glycerin inclusion in corn-soybean meal diets fed in 5 phases over a 138-d feeding trial.

[2]Evaluated 12 d postmortem according to National Pork Board Standards (NPPC, 2000). The marbling standards correspond to % intramuscular lipid.

[3]Japanese color bar 1 – 6 scale, 1 = extremely light, 6 = extremely dark (Sullivan et al. 2007).

[4]Higher L* values indicate a lighter color, higher a* values indicate a redder color, and higher b* values indicate a more yellow color (Sullivan et al. 2007).

[5]Average of 3 maximum force peaks.

[6]Scores on a 1 – 10 scale. Lower scores represent low degrees of characteristics, high scores represent high degrees of characteristics (Sullivan et al. 2007).

Table 7. Effect of crude glycerin on plasma metabolites pre-transport and at the time of harvest

	Pre-transport[1]			Harvest[1]				*P*-value		
Diet[2]	0	5	10	0	5	10	SEM	Diet	Time	D × T[3]
BUN mg/dL[4]	14.7	14.5	13.6	14.0	14.6	13.8	0.5	0.24	0.67	0.59
Cortisol, μg/dL	6.7	6.6	6.1	15.1	11.8	13.6	1.6	0.56	0.01	0.59
Glucose, mg/dL	101.8	99.0	98.0	138.6	143.4	140.3	4.6	0.91	0.01	0.70
Glycerol, μM	0.04	0.04	0.04	417.5	410.3	444.8	34.7	0.87	0.01	0.87
Lactate, mM	4.0	4.7	4.1	12.4	12.3	12.2	0.6	0.86	0.01	0.83
CPK, IU/L[5]	720.2	683.3	678.0	1,844.2	2,212.7	1,954.8	110.3	0.29	0.01	0.19

[1] Blood samples for plasma analysis were collected prior to transport to the abattoir and at the time of harvest immediately after electrical stunning.

[2] Dietary treatments were 0, 5, or 10% crude glycerin inclusion in corn-soybean meal diets fed in 5 phases over the 138-d feeding trial.

[3] D × T = interaction between diet and time

[4] BUN = blood urea nitrogen

[5] CPK = creatine phosphokinase

Table 8. Frequency of histological lesions in tissue of pigs fed crude glycerin[1]

	Diet[2]				
Lesion, % of tissues with lesion	0	5	10	SEM	*P*-value
Hecpatocellular pleomorphism	93.1	96.6	96.8	4.0	0.75
Portal hepatitis	41.3	34.5	45.1	9.2	0.70
Periportal fibrosis	27.6	17.2	12.9	7.3	0.34
Lymphoplasmacytic interstitial nephritis	41.4	41.4	48.4	9.4	0.82
Lymphoplasmacytic hepatitis	3.4	3.4	3.2	3.4	0.99
Lymphohistiocytic perineuritis	0.0	3.4	0.0	2.0	0.36
Hepatic lipidosis	3.4	0.0	0.0	2.0	0.35

[1] No gross lesions were observed in tissues harvested. One eye, liver, and kidney were collected from 29, 29, and 31 pigs for Diet 0, 5, and 10, respectively.

[2] Dietary treatments were 0, 5, or 10% crude glycerin inclusion in corn-soybean meal diets fed in 5 phases over a 138-d feeding trial.

CHAPTER 7. NON-SOLAR ENERGY USE AND 100-YEAR GLOBAL WARMING POTENTIAL OF IOWA SWINE FEEDSTUFFS AND FEEDING STRATEGIES

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ABSTRACT: Demand for non-solar energy and concern about the implications of fossil fuel combustion have encouraged examination of energy use associated with agriculture. The United States is a global leader in pig production and the U. S. swine industry is centered in Iowa. Feed is the largest individual input in pig production, but the energy consumption of the Iowa swine feed production chain has yet to be critically examined. This anlysis examines non-solar energy use and resulting 100-yr global warming potential (GWP) associated with the entire swine feed production chain, beginning with cultivation of crops and concluding with diet formulation. Five cropping sequences are considered and the non-solar energy use and accompanying 100-yr GWP associated with production of 13 common swine feed ingredients is estimated. A cropping sequence of corn-soybean-corn-oats under seeded with alfalfa delivers more NE and starch/MJ non-solar energy input than a corn-soybean or corn-corn-soybean sequence despite producing less total NE and starch/m^2. Two diet formulation strategies are considered for four crop sequence × diet type scenarios. The first formulation strategy (SIMPLE) does not include synthetic amino acids or phytase. The second (COMPLEX) reduces crude protein content of the diet by using L-lysine to meet SID lysine requirements of pigs and includes the exogenous enzyme phytase. Regardless of crop

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sequence × diet type scenario including the enzyme phytase is energetically favorable and reduces the potential excretion of phosphorus by reducing or removing inorganic phosphors from the complete diet. Including L-lysine reduces the crude protein content of the diet but requires more non-solar energy to deliver adequate SID lysine than simply feeding soybean meal. Replacing soybean meal with full-fat soybeans is not energetically beneficial under Iowa conditions. Swine diets including DDGS and crude glycerol require approximately 50% more non-solar energy inputs than corn-soybean meal diets or corn-soybean meal diets including oats. This study is not a complete life cycle assessment of pig production in Iowa but provides essential information on cultivation, processing, and manufacture of swine feed ingredients in Iowa that can be coupled with other models to estimate the non-solar energy use and 100-yr global warming potential of pig production in Iowa.

Keywords: Crop production, feed processing, swine feedstuffs

INTRODUCTION

Feed is the largest individual input in pig production systems. In the United States, pig diets are complete formulated mixes of several different ingredients, primarily corn and soybean meal. Iowa leads the United States in pork production as well as cultivation of corn and soybeans (USDA, 2009). Recently, production of biofuels—fuel grade ethanol from carbohydrates and monoakyl esters for biodiesel from lipids—has rapidly increased in the United States (NBB, 2008; RFA, 2009). Iowa also leads the United States in ethanol production (RFA, 2009) and is second in terms of biodiesel production capacity (NBB, 2008).

Processing grains and oilseeds into feed ingredients commonly fed to pigs require different techniques and energy inputs. Feed ingredients such as corn and oats are typically ground but generally require little additional manipulation. Other raw materials such as soybeans require multi-step processes to produce soybean meal and other potential diet components such as full-fat soybeans. Ground corn and soybean meal typically account for ≥ 95% of the mass of a typical pig diet. In the United States, the remaining 0–5% includes minerals, vitamins, synthetic amino acids, and enzymes. Growth in production of ethanol from corn grain and biodiesel from soy oil have increased the use of biofuel co-products, particularly dried distillers grains with solubles (DDGS) and to a lesser extent crude glycerol in pig diets. Crude glycerol is a co-product of biodiesel production, while DDGS is a co-product of ethanol distillery.

Nutrition recommendations for swine in the United States are currently based on metabolizable energy and apparent ileal digestible amino acids (NRC, 1998). A net energy (NE) system considers the amount of heat lost during digestion and subsequent deposition of nutrients in body tissue and is thus a more accurate estimate of the true energy content of an ingredient (Ewan, 2001; Moehn et al., 2005; Noblet, 2007). Discussion of the practicality and application of a net energy system is on-going among North American swine nutritionists (Moehn et al., 2005 ; Payne and Zijlstra, 2007; Zijlstra and Payne, 2008). At present standardized ileal digestibility is the most accurate basis for diet formulations in regards to amino acids availability (Gabert et al., 2001; Sauvant et al., 2004; Stein et al., 2007a; Stein et al., 2007b). More recent European recommendations are based on net energy and standardized ileal digestible amino acids (Whittemore et al., 2003). Feedstuff tables presenting the NE and SID amino acid content of feed ingredients are available (Whittemore et al., 2003; Sauvant et al., 2004).

With increasing attention being paid to energy in all aspects of agriculture, it is appropriate to re-examine the production of different swine feed ingredients and the potential impacts of different diet formulation strategies. This analysis examines the non-solar energy use and greenhouse gas emissions associated with the entire pig feed production chain. This begins with cultivation of crops and includes ingredient processing and manufacture, diet formulation, and diet metabolism within the pig. The crop–pig diet cycle is completed with return of nutrients in pig manure back to cropland. This analysis examines different crop production scenarios, processes for preparing diet ingredients, and efficacy of various formulation strategies to minimize non-solar energy use, optimize nutrient cycling, and minimize 100-year global warming potential from emissions associated with pig feed production.

MATERIALS AND METHODS

Crop production. A crop production model representative of conditions seen in Iowa was developed and used to evaluate different crop rotation scenarios (Lammers, 2009a). Models are simplifications of reality and thus are inherently imprecise. Models can be useful for predicting trends and relative differences between several systems. The purpose is not to detail every input and variable that may affect crop production and resulting environmental impact. Rather simplifying assumptions are made with the goal of developing a functional representation of crop production and resulting environmental impacts under the context of pig production in Iowa. The crop production model is not designed to accurately predict absolute impacts. Rather the model is intended to predict the relative magnitude and direction of outcomes resulting from different actions and choices.

Five crop sequences were selected for examination. They are: continuous corn (C-C), corn-soybean (C-S), corn-corn-soybean (C-C-S), corn-soybean-corn-oat under seeded with alfalfa (C-S-C-O), and corn-soybean-corn-oat under seeded with alfalfa-alfalfa (C-S-C-O-A). The first 3 sequences are currently typical in Iowa and across the Midwest United States. The last 2 rotations are proven alternatives that may reduce total non-solar energy use and better facilitate nutrient cycling within crop production. Initial conditions and model assumptions for cultivation of the different crop rotations were developed in consultation with Iowa farmers, Iowa State University researchers, extension publications, and peer-reviewed research articles. In practice alfalfa may be planted once and harvested for a period of 3–5 years. However alfalfa hay is not a common diet component in pig diets, nor is it well utilized by swine. The purpose of this model is to examine crop production in the context of pig production and as such it was assumed that only 1 year of alfalfa hay would be produced on a given area before it returns to production of grain or oilseeds more commonly fed to pigs. Both the C-C and C-S-C-O-A sequences may not be practical for total and complete swine feed production, however we included these two sequences in our anlayis in order to more fully examine and compare the C-S, C-C-S, and C-S-C-O sequences.

Three main types of non-solar energy inputs were considered: diesel fuel, liquefied petroleum gas, and electricity. Emission of 3 greenhouse gases— CO_2, CH_4, and N_2O—were estimated based on fuel type (IPCC, 2006; EPA, 2008). Standardized 100-yr GWP for the three gases were used to calculate 100-year global warming potential by energy type expressed in terms of CO_2 equivalents (IPCC, 2007). Diesel fuel is the most commonly used energy source for operating crop production equipment and transporting grain. Diesel fuel use is often reported in terms of volume per time, volume per area, or volume per distance.

To calculate the energy consumed as diesel fuel, an energy density of 38.46 MJ/L was assumed for diesel fuel (Downs and Hansen, 1998). For every GJ of diesel fuel combusted by agricultural equipment, an estimated emission of 82.73 kg CO_2 equivalents occurs (IPCC, 2006, 2007). Liquefied petroleum gas is used as a major feedstock and source of energy in the manufacture of synthetic fertilizers and pesticides (Bhat et al., 1994). It is also commonly used to dry grain on-farm (Bern, 1998; Wilcke, 2004). It is estimated that 63.15 kg CO_2 equivalents are released for every GJ of energy originating as liquefied petroleum gas (IPCC, 2006, 2007). Domestic electricity generation emission factors for Iowa (EPA, 2008) were used to estimate the 100-yr global warming potential resulting from use of electricity. It is estimated that 229.32 kg CO_2 equivalents are released for every GJ of electrical energy used (IPCC, 2007; EPA, 2008).

Gross energy (GE) of all production represents the energy that could be gained by simply combusting all grain, oilseed, and biomass produced by a given crop sequence. Net energy (NE) represents the portion of gross energy that is available for a pig to use for growth and maintenance from a particular feedstuff (Ewan, 2001; Whittemore, 2006). Net energy most closely represents the true energy value of a feedstuff relative to pig production and is the energy value of most interest to swine nutritionists (Ewan, 2001; Whittemore et al., 2003; Whittemore, 2006). Starch concentration is another important measure of a product's suitability for human food (Quezada-Cavillo et al., 2006) or pig feed (Sauber and Owens, 2001; Whittemore, 2006). Sauvant et al. (2004) presents the GE, NE available to pigs, and the starch content of many feed ingredients. The GE of wheat straw is 16.9 MJ/kg, (91.4% dry matter) (Sauvant et al., 2004) and our analysis assumes oat straw is equivalent to wheat straw. Corn stover was assumed to have a GE value of 14.2 MJ/kg at 15% moisture

(Pordesimo et al., 2005). It was assumed that oat straw and corn stover are of very limited value as food or feedstuffs and that NE and starch content is effectively zero. Crop production model results and literature values were used to calculate GE, NE available to growing pigs, and total starch production for each crop production sequence.

Feed ingredient processing and manufacture. Feed ingredients such as corn require little manipulation beyond grinding. Alternatively, converting raw soybeans into soybean meal and soy oil requires multi-step processes. An inventory of raw material inputs, processing activities, estimated transportation distances of material inputs and finished ingredients, and non-solar energy use for 13 feed ingredients was prepared and has been detailed elsewhere (Lammers, 2009b). This inventory is summarized in table 1 and was used in combination with diet formulations to calculate non-solar energy use and 100-yr GWP associated with manufacturing swine feed adequate to produce one, 136.0 kg market pig. Primary feed ingredients—grains, soybean meal, biofuel co-products—typically account for ≥ 95% of the mass of pig diets. The remaining mass of the diet includes minerals, vitamins, synthetic amino acids, and enzymes. Our examination of the micro-feed ingredients focuses on ground limestone, salt, and monocalcium phosphate (MCP) because these three ingredients account for most of the mass among micro-ingredients. The enzyme phytase and synthetic amino acids L-lysine and DL-methionine are also included because they have an impact on phosphorus and nitrogen utilization and cycling within pig production systems that is disproportionate to their relative mass.

Diet formulation and metabolism. Diet formulations that have been demonstrated to be nutritionally adequate according to NRC recommendations (Holden et al., 1996; NRC, 1998; Lammers et al., 2008) were entered into a spreadsheet that recalculated nutritional content based on feed ingredient tables presented by Sauvant et al. (2004). Two reference diets were for adult animals—one for gestating sows and one for lactating sows (Holden et al., 1996). Five reference diets were for growing pigs and matched the corn-soybean meal control diets fed in a previous study (Lammers et al., 2008). Reference diets and estimated nutrient intake associated with production of one 136.0 kg market pig is presented as table 2. The ratio of SID lysine to NE as well as the ratio of available phosphorus to NE were calculated from the reference diets and used to formulate a set of baseline diets (SIMPLE) for this analysis. This set of diets does not include synthetic amino acids or exogenous enzymes.

Including synthetic amino acids and the enzyme phytase affects nitrogen and phosphorus utilization by the pig and impacts the overall nutrient cycling of pig feed production. A second set of diets (COMPLEX) were formulated to include phytase and synthetic amino acids. The desired ratio of threonine to NE and tryptophan to NE for a given diet were calculated based on the ideal amino acid ratio concept (NRC, 1998; Lewis, 2001; Whittemore et al., 2003). COMPLEX Diets were first formulated to provide adequate threonine and tryptophan. The synthetic amino acids DL-methionine and L-lysine were then added as needed to provide adequate methionine and lysine. Feeding the enzyme phytase enables utilization of plant source phosphorus by pigs and allows diets containing reduced amounts of inorganic phosphorus to be nutritionally adequate. Based on previous reports (Veum et al., 2006; Veum and Ellersieck, 2008; Emiola et al., 2009), MCP was excluded from diets containing phytase unless the total phosphorus provided by the final diet (g total phosphorus : kJ NE) was not ≥ 100% of the available phosphorus presented by the reference diets.

Within each general formulation scheme (SIMPLE and COMPLEX) four different strategies were considered. The first (Corn-SBM) represents what is typical practice in Iowa and consists primarily of corn and soybean meal. The second (Oat-SBM) is a corn-soybean meal diet that includes oats. Diets for growing pigs were formulated to include 4% oats and sow diets included up to 80% oats by mass for the Oat-SBM strategy. The third diet strategy (Oat-FFSB) is a corn-based diet that includes oats and replaces soybean meal with full-fat soybeans. An earlier study in Denmark reported replacing soybean meal with peas and rapeseed cake reduced non-solar energy inputs for swine diet manufacture by 22% (Ericksson et al., 2005). The Oat-FFSB diet strategy was designed to examine the efficacy of alternative sources of protein-feed ingredients in Iowa. Full-fat soybeans were used as the primary source of amino acids and soybean meal was removed from all diets. Diets for growing pigs and sows were allowed to include up to 10 and 80% oats respectively. The final diet strategy (Co-products) is a corn-soybean meal diet that includes maximal amounts of DDGS and crude glycerol. Diets for growing pigs were allowed to include up to 25% DDGS and diets for sows included 35–40% DDGS. All diets under the Co-products formulation strategy included 10% crude glycerol.

Diet formulation strategies were then considered under the context of selected crop sequences. Ingredient lists from each formulation strategy were combined with non-solar energy and 100-yr GWP values associated with processing feed ingredients and non-solar energy and 100-yr GWP associated with cultivation of different crops in selected sequences. For each cropping sequence × diet formulation scenario, the non-solar energy and 100-yr GWP required to grow, manufacture, and deliver adequate feed (approximately 4,300 MJ

NE, 2.8 kg SID lysine, and 1.2 kg available phosphorus) to produce one 136.0 kg market pig was determined.

RESULTS AND DISCUSSION

Table 1 reports the non-solar energy use and resulting 100-yr GWP associated with producing and delivering 13 swine feed ingredients in Iowa. This inventory is not a complete life cycle assessment of swine feed but can be linked with crop and pig production models to estimate the ecological impacts of raising pigs. The last compilation of multiple swine feed ingredients was published in 1978 and was specific to Australia (LaHore and Croke, 1978). More recent examinations have considered 1 or 2 individual ingredients under European conditions (Binder, 2003; Nielsen et al., 2006; Nielsen and Wenzel, 2006; Dalgaard et al., 2008). The feed table included in this report is not a complete listing of all ingredients commonly fed in Iowa, however it is starting point for future examinations of non-solar energy use associated with other swine feed ingredient production in Iowa and the United States and can be used for life cycle analysis of pig production in the Midwest United States.

Tables 3 and 4 summarize the non-solar energy and 100-yr GWP of individual crops within different cropping sequences in Iowa. Production of corn grain requires the most energy per unit of land area but also produces the largest quantity of grain of any crop examined (Lammers, 2009a). This results in corn requiring less non-solar energy per kg grain than soybeans and oats in most cropping sequences. Increasing the complexity of cropping sequences allows reduction in synthetic fertilizers applied to corn while maintaining or enhancing productivity. This results in corn grain grown in the C-S-C-O-A sequence requiring 29% less non-solar energy compared to corn grain grown in the C-C sequence. A similar but less pronounced trend is seen in soybeans. As expected, the 100-yr GWP of individual crops within different crop sequences closely follows non-solar energy use.

Increasing crop sequence complexity reduces non-solar energy use and 100-yr GWP for individual crops within a sequence while maintaining or increasing crop output/m^2 (Lammers, 2009a). This advantage requires foregoing the opportunity to maximizing production of a single crop per total land area. For example, the crop production model assumes that corn raised in C-C produces 1.13 kg/m^2 while corn raised in C-S produces 1.26 kg/m^2 (Lammers, 2009a). If 100 m^2 is managed as C-C, 113 kg corn grain will be produced, alternatively if the same 100 m^2 is managed as C-S only 63 kg corn grain will be produced. This illustrates the importance of not only considering individual crops within a sequence, but the sum productivity of entire crop sequences.

The total non-solar energy inputs, 100-yr GWP, and productivity of 5 complete crop sequences in Iowa are summarized as table 5. Continuous corn delivers the most GE, NE and starch/m^2, but also requires the most non-solar energy input of any sequence examined. The most complex sequence—C-S-C-O-A—requires the least non-solar energy input/m^2 but also delivers the least total GE, NE, and starch. The C-S sequence results in the most NE/ MJ non-solar energy input. Our analysis assumes no NE is gained from alfalfa by pigs. Despite this assumption, the complex C-S-C-O-A sequence produces more MJ NE/ MJ non-solar energy input than continuous corn. Alfalfa hay certainly has value, particularly as feed for horses or ruminants, however expanding our analysis to include other species of livestock is beyond the scope of this report. The C-C-S sequence produces the second most Starch/MJ non-solar energy. The C-C-S and C-S-C-O-A sequences produce similar amounts of NE/MJ non-solar energy. The C-S-C-O sequence produces more starch/MJ non-solar energy but less NE/MJ non-solar energy than the C-S sequence.

The calculated analysis of four formulation strategies without the use of synthetic amino acids and phytase (SIMPLE) is summarized in table 6. The diet analysis presented is a weighted average of all feed associated with production of one 136.0 kg market pig. This includes 5 diets fed to growing pigs as well as the lactation and gestation feed required to produce 1 pig. Table 7 details the same formulation strategies but allows use of synthetic amino acids and the exogenous enzyme phytase (COMPLEX). As expected the inclusion of L-lysine reduces g crude protein intake/ MJ NE. Intake of crude protein content from diets containing L-lyisne is 83–91% of the crude protein intake from the SIMPLE diet formulations. Including the exogenous enzyme phytase consistently enables reduction of total phosphorus in diet formulations. The benefits of phytase are less pronounced when formulating diets with ≥ 25% DDGS. This is because DDGS has sufficient available phosphorus to exclude most MCP from the SIMPLE diet formulation. The advantage of including phytase is the ability to reduce the amount of MCP and other inorganic sources of phosphorus in the diet. Because the SIMPLE, Co-products diet formulation already has < 1% MCP, adding phytase does not reduce MCP inclusion as much as in other diet formulation.

Eight crop sequence × diet formulation scenarios are presented in table 8. Our analysis did not compare every possible crop sequence × diet formulation combination. Rather we focused our analysis on combinations of most interest. The baseline scenario is a corn-soybean meal diet and a C-S cropping sequence. This combination is representative of current Iowa practice. A slight modification of current practice would be adoption of the C-S-C-O sequence with an accompanying inclusion of oats in the diets fed to pigs. A third alternative considers the potential of feeding full-fat soybeans to pigs. Full-fat soybeans are not typically fed to pigs. However there is interest in increasing on-farm processing of feedstuffs and roasting soybeans is a method of processing soybeans that can easily be done on-farm in Iowa. The diet that includes full-fat soybeans is nested within the C-S-C-O sequence rather than the C-S sequence because producers most interested in on-farm roasting of soybeans are assumed to also be more interested in diversifying cropping sequences than others. The final crop sequence × diet formulation combination is a C-C-S sequence that includes production of the biofuels and feeding of biofuel co-products.

Inclusion of L-lysine and exogenous phytase is typical of conventional pig production in the United States. The COMPLEX formulation strategy incorporates this practice. The COMPLEX formulation strategy requires less non-solar energy input/ MJ NE delivered to pigs for most crop sequence × diet scenarios. The COMPLEX formulation strategy reduces non-solar energy input/ MJ NE by 3–7% for each diet type. The exception is the Co-product diet type. The COMPLEX formulation of the Co-product diet requires 1.8% more non-solar energy input than the SIMPLE formulation of the Co-product diet. As expected 100-yr GWP follows input energy. Including phytase and L-lysine reduces 100-yr GWP associated with pig diet production by 40–90% depending on the diet type.

The COMPLEX corn-soybean meal diet requires less non-solar energy input/ MJ NE delivered to pigs than the SIMPLE formulation. Adding L-lysine to a corn-soybean meal diet allows removal of approximately 25% of the soybean meal in the diet. This results in a reduction of energy needed to produce soybeans, but an increase in energy to produce L-lysine. For the corn-sbm baseline, removing some soybeans and adding L-lysine was not energetically favorable. The SIMPLE diet requires expenditure of 30.5 kJ of non-solar energy to provide adequate SID lysine as soybean meal. The COMPLEX diet requires expenditure of 30.7 kJ of non-solar energy to provide adequate SID lysine as soybean meal and L-lysine. Although not energetically advantageous, adding L-lysine to the diet allows dramatic reduction in the total crude protein delivered to the animal. This in turn reduces the potential for nitrogen excretion by pigs into the environment. Increasing pork production per unit of feed nitrogen delivered to pigs has been a goal of United States pork producers and the inclusion of L-lysine supports that. However inclusion of L-lysine comes at an energetic cost that is not offset by equal or more reductions in energy expended to provide soybean meal or other protein sources. This may ultimately limit the utility of diets formulated to include synthetic amino acids when considered from a crop × livestock systems perspective.

Feeding phytase allows nearly complete removal of MCP from pig diets. Because MCP requires a large amount of non-solar energy to produce, its near elimination from diet formulations greatly reduces non-solar energy inputs for complete diet production. Phytase also requires a large amount of non-solar energy to produce, but the benefits of phytase can be achieved by including very small amounts of the exogenous enzyme in the diet. For example, the SIMPLE Oat-SBM diet contains 0.92% MCP by mass at an energetic cost of 13.0 kJ non-solar energy input/MJ NE. Adding 0.01% phytase to the diet allows removal of all MCP and only requires 0.4 kJ non-solar energy input/MJ NE. This translates into a savings of 12.6 kJ non-solar energy/ MJ NE pig diet for the Oat-SBM diet type. Inclusion of phytase in pig diets enables diets lower in total phosphorus to be nutritionally adequate and may lower phosphorus excretion by pigs (Veum et al., 2006; Veum and Ellersieck, 2008; Emiola et al., 2009). The additional energetic cost of including phytase is more than off-set by reductions in the non-solar energy input required if providing adequate available phosphorus as MCP.

The Oat-SB diet type required 8% more non-solar energy input/MJ NE than the Corn-SBM diet type for both formulation strategies. As in the Corn-SBM diet type, the main energetic advantage of the COMPLEX formulation strategy was removal of MCP from the diet. Adding L-lysine reduced the crude protein content of the diet, but also increased the energy cost of supplying SID lysine as compared to the SIMPLE formulation strategy.

The Oat-FFSB diet type is not energetically favorable compared to the Corn-SBM and Oat-SBM approaches. Roasting of soybeans requires large inputs of non-solar energy and does not deliver proportional benefits in terms of total non-solar energy input/MJ NE delivered to pigs. Previous European examinations of pig production have suggested that avoidance of soybean meal in pig diets is energetically and environmentally beneficial (Ericksson et al., 2005). Our results disagree with those conclusions. Soybean meal used in the Danish study was imported from South America (Ericksson et al., 2005) but our study assumed soybean processing occurs within the state of Iowa (Lammers, 2009b). Imported soybean meal is a major source of amino acids for European swine diets (Ericksson et al., 2005; Dalgaard et al., 2008). Given Iowa's leadership in U. S. soybean production (USDA, 2009) and processing (Hardy, 2009) some of the previously reported advantages of displacing soybean meal with alternative protein sources (Ericksson et al., 2005) may not apply to Iowa. Including L-lysine in the Oat-FFSB diet was energetically favorable due to reduced inputs of full-fat soybeans. The SIMPLE diet formulation required 73.1 MJ non-solar energy input to provide adequate SID lysine in the form of full-fat soybeans. The

COMPLEX diet formulation required 64.6 MJ non-solar energy input to provide adequate SID lysine as full-fat soybeans and L-lysine.

Diets containing ≥ 25% DDGS and 10% crude glycerol required more non-solar energy input/MJ NE than any other diet scenario. The production energy of co-product feeds is larger then the non-solar energy needed to grow and process other major feed ingredients. For example if we assume a C-S sequence, 1.0 kg of ground corn requires 1,894 kJ and 1.0 kg of soybean meal require 2,394.4 kJ non-solar energy input. Alternatively DDGS requires 4,700 kJ/kg and crude glycerol requires 2,200 kJ/kg. The NE of the four ingredients is also different—11.1, 8.4, 7.0, and 9.9 MJ/kg— for corn grain, soybean meal, DDGS, and crude glycerol respectively. Thus each MJ of NE from corn grain and soybean meal requires 171 and 285 kJ non-solar energy respectively while each MJ of NE from DDGS and crude glycerol require 671 and 224 kJ non-solar energy respectively. If return of NE for pigs/kJ non-solar energy input is the only concern, feeding biofuel co-products is not favorable. However if biofuels are produced, including co-products in swine diets might be economical for individual producers.

Unlike the other diet types, the COMPLEX formulation strategy required 1.8% more non-solar energy/MJ NE than the SIMPLE formulation. This is a result of 2 factors. The first is the COMPLEX diet includes L-lysine. L-lysine reduces the crude protein content of the diet but increases the non-solar energy needed to provide adequate SID lysine compared to soybean meal. The second factor has to do with the nature of DDGS. Fermentation of corn grain results in the phosphorus present in DDGS being more available to pigs than phosphorus in corn. Increasing the availability of plant-source phosphorus means little MCP is needed in the SIMPLE diet formulation of the Co-product diet type. The main energetic advantage of the COMPLEX diet formulation for the other diet types was removal of approximate 13.0 kJ non-solar energy input associated with providing available phosphorus as MCP. With less MCP in the SIMPLE Co-product diet to remove the energetic benefits achieved by adding phytase and removing MCP are overcome by the increase in non-solar energy used to deliver SID lysine.

Including DDGS and crude glycerol may require more non-solar energy than simply feeding corn grain and soybean meal, but for individual operations adding biofuel co-products may be economical. Adding phytase to diets and reducing or removing MCP reduces the non-solar energy cost of swine feed and may reduce phosphorus excretion from the pig. This is clearly a double benefit of phytase. The net effect of feeding L-lysine is less clear cut. Adding L-lysine reduces the crude protein content of diets while providing adequate SID lysine to pigs and might reduce excretion of nitrogen by pigs. However this environmental benefit is achieved at a cost of increased non-solar energy inputs—first to provide SID lysine in as L-lysine to pigs and secondly by increasing the need for synthetic nitrogen for crop production. Further examination of the interactions among non-solar energy use for synthetic fertilizers and different strategies to deliver adequate SID lysine to pigs is warranted and should be a high priority for individuals considering the non-solar energy use and environmental impacts of pig production systems.

The current study is not a complete life cycle assessment of pig production in Iowa. However the presented inventory of non-solar energy and 100-yr GWP associated with growing and processing swine feed ingredients provides essential information for life cycle assessment of pig production. Results from this project can be combined with other studies to more fully understand the non-solar energy use and 100-yr GWP of Iowa swine production.

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Table 1. Energy use and resulting 100-yr global warming potential associated with producing and delivering swine feed ingredients to feed mill and mixing formulated swine diets in Iowa[1].

Ingredient	Production Energy[2] kJ/kg	100-yr GWP[2] g CO_2 equivalents/kg
Ground corn	24.0	4.3
Ground oats	24.0	4.3
Full-fat roasted soybeans	597.9	46.7
Soybean meal	501.0	39.9
Soy oil	421.0	33.6
DDGS[3]	4,700.0	86.4
Crude glycerol[4]	2,200.0	168.3
Ground limestone[5]	2,545.0	173.4
Salt[5]	1,635.0	279.8
Monocalcium phosphate[6]	13,800.0	1,104.4
Phytase[7]	40,000.0	2,000.0
L-Lysine	52,170.0	1,642.2
DL-Methionine[8]	88,000.0	5,557.2
Mixing and delivery of diet	10.5	1.2

[1] Values from Lammers (2009b) unless otherwise noted.

[2] Does not include energy use or 100-yr global warming potential (GWP) associated with cultivation and storage of grains and oilseeds.

[3] Values include energy and 100-yr GWP required to produce 3.3 kg corn grain in C-S sequence. Values exclude NE of 3.3 kg corn grain not fed to pigs, the gross energy of 1.4 L ethanol that is co-produced, and the potential displacement of other transportation fuels by ethanol. Values assume 0% capture of CO_2 produced by fermentation.

[4] Values include energy and 100-yr GWP required to production 14.2 kg soy oil from C-S sequence. Values exclude NE of 14.2 kg soy oil not fed to pigs, the gross energy of 12.7 L of biodiesel that is co-produced, and the potential displacement of other transportation fuels by biodiesel.

[5] (LaHore and Croke, 1978).

[6] (Nielsen and Wenzel, 2006).

[7] (Nielsen et al., 2006).

[8] (Binder, 2003).

Table 2. Nutrient content of reference diets and estimated nutrient intake associated with production of one, 136.0 kg market pig[1].

Diet	Feed intake[2], kg	Net Energy MJ/kg	Standardized ileal digestible Lysine, g/kg	Available Phosphorus, g/kg
Phase 1	10.2	10.15	12.21	6.11
Phase 2	16.8	9.99	10.77	5.42
Phase 3	57.8	10.16	9.54	4.04
Phase 4	92.3	10.27	7.57	3.29
Phase 5	181.4	10.52	5.90	2.49
Gestation	37.0	10.72	4.29	5.06
Lactation	15.6	10.29	8.59	5.49
Totals[3]	411.1	4.27	2.80	1.28

[1] Reference diets from Lammers et al. (2008) and Holden et al. (1996).

[2] Feed intake assumptions from Lammers et al. (2009), includes death loss of 2.9 and 3.9% in nursery and grow-finish respectively.

[3] Total kg feed intake; GJ net energy; kg standardized ileal digestible lysine, and kg available phosphorus associated with production of one 136.0 kg market pig.

Table 3. Calculated non-solar energy use and associated with production of grains, oilseeds, and biomass from different cropping sequences in Iowa[1].

	Cropping Sequence[2]				
Product	C-C	C-S	C-C-S	C-S-C-O	C-S-C-O-A
Corn grain, kJ/kg	2,116.8	1,870.0	1,975.7	1,785.5	1,510.7
Corn stalks, kJ/kg	55.6	53.4	53.4	53.4	53.4
Soybeans, kJ/kg	na	1,893.4	1,878.7	1,878.7	1,849.7
Soybean meal[3], kJ/kg	na	1,079.2	1,070.9	1,070.9	1,054.3
Soy oil[3], kJ/kg	na	814.2	807.8	807.8	795.4
Oat grain, kJ/kg	na	na	na	2,754.2	2,754.2
Oat straw, kJ/kg	na	na	na	37.1	37.1
Alfalfa hay, kJ/kg	na	na	na	na	1,355.0

[1] Based on Lammers (2009a).

[2] C-C = continuous corn; C-S = corn, soybean; C-C-S = corn, corn, soybean, C-S-C-O = corn, soybean, corn, oat under seeded with alfalfa; C-S-C-O-A = corn, soybean, corn, oat under seeded with alfalfa, alfalfa hay.

[3] Assumes soybeans are processed into soybean meal (80% of soybean mass) with NE of 8.4 MJ/kg and 17% soybean oil (17% of soybean mass) with NE of 29.8 MJ/kg. A processing loss of 3% soybean mass is also assumed. Soybean cultivation energy allocated based on NE of final product mass (57% attributed to soybean meal, 43% attributed to soy oil) (Lammers, 2009b).

Table 4. Calculated 100-yr global warming potential (g CO_2 equivalents/kg) associated with production of grains, oilseeds, and biomass from different cropping sequences in Iowa[1].

	Cropping Sequence[2]				
Product	C-C	C-S	C-C-S	C-S-C-O	C-S-C-O-A
Corn grain, g CO_2/kg	151.7	133.5	140.6	127.8	109.4
Corn stalks, g CO_2/kg	4.6	4.3	4.3	4.3	4.3
Soybeans, g CO_2/kg	na	140.8	139.5	139.5	137.4
Soybean meal[3], g CO_2/kg	na	80.3	79.5	79.5	78.3
Soy oil[3], g CO_2/kg	na	60.5	60.0	60.0	59.1
Oat grain, g CO_2/kg	na	na	na	216.0	216.0
Oat straw, g CO_2/kg	na	na	na	2.9	2.9
Alfalfa hay, g CO_2/kg	na	na	na	na	104.0

[1] Based on Lammers (2009a).

[2] C-C = continuous corn; C-S = corn, soybean; C-C-S = corn, corn, soybean, C-S-C-O = corn, soybean, corn, oat under seeded with alfalfa; C-S-C-O-A = corn, soybean, corn, oat under seeded with alfalfa, alfalfa hay.

[3] Assumes soybeans are processed into soybean meal (80% of soybean mass) with NE of 8.4 MJ/kg and 17% soybean oil (17% of soybean mass) with NE of 29.8 MJ/kg. A processing loss of 3% soybean mass is also assumed. Soybean cultivation energy allocated based on NE of final product mass (57% attributed to soybean meal, 43% attributed to soy oil) (Lammers, 2009b).

Table 5. Summary of production, non-solar energy inputs, and 100-year global warming potential for 5 crop sequences[1,2].

Sequence	C-C	C-S	C-C-S	C-S-C-O	C-S-C-O-A
Gross energy, MJ/m^2	31.25	21.25	25.81	22.06	20.62
Net energy, MJ/m^2	12.27	8.89	10.52	8.79	7.76
Starch, g/m^2	708.40	394.95	526.60	432.94	346.35
Non-solar energy, MJ/m^2	2.44	1.57	1.94	1.66	1.43
100-yr GWP[3], g CO_2 equivalents/m^2	175.70	113.10	139.3	119.8	105.1
Output Ratios					
Gross energy : non-solar energy	12.81	13.54	10.95	13.29	14.42
Net energy : non-solar energy	5.03	5.66	5.42	5.29	5.43
Starch : non-solar energy	290.33	251.56	271.44	260.81	242.20
Gross energy : 100-yr GWP	0.18	0.19	0.19	0.18	0.20
Net energy : 100-yr GWP	0.07	0.08	0.07	0.07	0.07
Starch : 100-yr GWP	4.03	3.49	3.78	3.61	3.30

[1] From Lammers (2009a).

[2] CC= continuous corn, C-S = corn-soybean; C-C-S = corn-corn-soybean; C-S-C-O = corn, soybean, corn, oat under seeded with alfalfa; C-S-C-O-A = corn, soybean, corn, oat under seeded with alfalfa, alfalfa hay

[3] 100-yr GWP = 100-year global warming potential

Table 6. Calculated analysis and ingredients for 4 SIMPLE[1] diet formulations required for production of one, 136.0 kg market pig.

	Formulation strategy			
Ingredient	Corn-SBM	Oat-SBM	Oat-FFSB	Co-products
Corn,%	76.84	63.12	45.64	44.04
Soybean meal, %	19.85	18.03	0	15.89
Oats, %	0	15.57	20.93	0
Full-fat soybeans, %	0	0	29.66	0
DDGS, %	0	0	0	26.88
Crude glycerol, %	0	0	0	10.00
Ground limestone, %	2.02	2.14	2.57	2.98
Salt, %	0.29	0.22	0.28	0
Monocalcium phosphate, %	1.00	0.92	0.92	0.21
Total	100.00	100.00	100.00	100.00
Estimated feed intake, kg	417.35	435.31	425.25	465.73
Analysis				
NE, MJ/kg	10.24	9.81	10.05	9.17
SID Lysine : NE, g/MJ	0.66	0.66	0.66	0.66
Available P : NE, g/MJ	0.30	0.30	0.30	0.31
Crude protein : NE, g/MJ	15.24	15.44	16.11	19.26
Total P : NE, g/MJ	0.54	0.55	0.55	0.53

[1] Diets formulated to have equal ratios of standardized ileal digestible (SID) lysine to NE and available phosphorus (available P) to NE. No synthetic amino acids or exogenous enzymes included.

Table 7. Calculated analysis and ingredients for COMPLEX[1] diet formulations required for production of one, 136.0 kg market pig.

	Formulation strategy			
Ingredient	Corn-SBM	Oat-SBM	Oat-FFSB	Co-products
Corn,%	83.17	68.04	52.34	51.99
Soybean meal, %	14.91	14.16	0	8.98
Oats, %	0	15.88	21.15	0
Full-fat soybeans, %	0	0	24.34	0
DDGS, %	0	0	0	26.66
Crude glycerol, %	0	0	0	10.00
Ground limestone, %	1.49	1.53	1.75	2.12
Salt	0.22	0.24	0.30	
Monocalcium phosphate, %	0.03	0	0	0
L-lysine, %	0.17	0.14	0.11	0.24
Exogenous phytase[2], %	0.01	0.01	0.01	0.01
Total	100.00	100.0	100.0	100.0
Estimated feed intake, kg	405.19	423.83	417.01	450.31
Analysis				
NE, MJ/kg	10.54	10.08	10.24	9.49
SID Lysine : NE, g/MJ	0.66	0.66	0.66	0.66
Available P : NE, g/MJ	0.30	0.30	0.30	0.30
Crude protein : NE, g/MJ	13.22	13.77	14.64	16.06
Total P : NE, g/MJ	0.32	0.31	0.32	0.44

[1] Diets formulated to have adequate threonine. Synthetic lysine and methionine added as needed to meet requirements.

[2] Exogenous phytase assumed to have phytase activity of 5,000 U/g material.

Table 8. Non-solar energy inputs1 and 100-yr global warming potential associated with feeding one 136.0 kg market pig from select crop sequence × diet formulation strategies.

Crop sequence[2]	C-S		C-S-C-O		C-S-C-O		C-C-S	
Diet Type[3]	Corn-SBM		Oat-SB		Oat-FFSB		Co-product	
Formulation strategy[4]	S	C	S	C	S	C	S	C
Corn, kJ/MJ NE	142.2	149.4	116.4	122.1	82.2	92.5	96.0	109.5
Oats, kJ/MJ NE	0	0	44.1	43.8	57.9	57.3	0	0
Soybean meal, Kj/MJ NE	30.5	22.2	28.9	22.1	0	0	27.2	15.0
Full-fat soybeans, kJ/MJ NE	0	0	0	0	73.1	58.8	0	0
L-lysine, kJ/MJ NE	0	8.6	0	7.1	0	5.8	0	13.1
DDGS, kJ/MJ NE	0	0	0	0	0	0	137.7	132.1
Crude glycerol, kJ/MJ NE	0	0	0	0	0	0	24.0	23.2
Limestone, kJ/MJ NE	5.0	3.6	5.6	3.9	6.5	4.4	8.3	5.7
Salt, kJ/MJ NE	0.5	0.3	0.4	0.4	0.5	0.5	0	0
Monocalcium phosphate, kJ/MJ NE	13.4	0.4	13.0	0	12.6	0	3.2	0
Phytase, kJ/MJ NE	0	0.4	0	0.4	0	0.4	0	0.4
Mix and deliver, kJ/MJ NE	1.0	1.0	1.1	1.0	1.0	1.0	1.1	1.1
Total input energy, kJ/MJ NE	192.6	185.9	209.4	200.8	233.8	220.7	297.5	300.1
Total 100-yr GWP[5], g CO_2/MJ NE	14.3	13.3	38.9	10.0	17.7	15.4	23.5	13.8

CHAPTER 8. OPTIMIZING USE OF NON-SOLAR RESOURCES IN PIG PRODUCTION: AN EXAMINATION OF IOWA SYSTEMS

A paper to be submitted to *Agricultural Systems*

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ABSTRACT

Most published research concerning non-solar energy use by swine production systems has been conducted in Europe and does not extensively examine different housing scenarios. This paper compares non-solar energy use for pig production options in Iowa. The baseline system produces 15,600 pigs annually using confinement facilities and a corn-soybean cropping sequence. Diet formulations for the baseline system include synthetic amino acid L-lysine and exogenous phytase. The baseline system represents the majority of current pork production systems in Iowa and the Upper Midwest where the majority of U.S. swine are produced. The baseline system is designed to minimize land-surface area requirements and encourage maximal pork production per unit of feed net energy and standardized ileal digestible lysine fed to pigs. Selected combinations of facility type × diet formulation × crop sequence scenarios were examined and compared. The baseline system for swine production in Iowa is estimated to require 7.1 MJ non-solar energy/kg of live weight pig produced. Emissions of 587 g CO2 equivalents/kg live weight are also associated with the Iowa swine production systems. An alternative system that uses hoop barns for

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grow-finish pigs and gestating sows would require only 6.9 MJ non-solar energy/kg live weight and result in emission of 516 g CO_2 equivalents/kg, a 3 and 12% reduction respectively. Using hoop barns for swine production requires more feed and thus more non-solar energy to grow and process feed ingredients. However the savings in non-solar energy associated with operating hoop barn-based swine systems relative to conventional confinement systems offsets those inputs. When assessing swine production systems, diet type and feed ingredient processing is the major influence on non-solar energy use and 100-yr global warming potential, but facility type also must be considered.

1. Introduction

Life cycle assessment (LCA) of swine production has been concentrated in Europe, particularly Denmark (Halberg, 1999; Zhu and van Ierland, 2004; Basset-Mens and van der Werf, 2005; Ericksson et al., 2005; Williams et al., 2006; Dalgaard et al., 2007; Meul et al., 2007). There are fundamental differences between European and United States swine production that limits the application of European results to inform decision making by pig producers in the United States. European swine diets typically include more variety of feed ingredients and often include high amounts of small grains such as barley. Peas, rapeseed cake, and soybean meal are all commonly used as protein sources in European swine diets. In the United States, swine diets are almost entirely comprised of corn and soybean meal. Growing pigs are usually limit fed in Europe but fed ad libitum in the United States. Feeding pelleted or liquid feeds is Europe is common while in the United States almost all diets are ground and fed dry. Some farms provide water at the feeder, encouraging consumption of a wet-dry feed, but this strategy is very different from liquid feeding systems seen in Europe.

Finally climate conditions and primary environmental concerns differ between Europe and the United States.

United States swine production is centered in Iowa (USDA, 2009). Iowa is also a leader in production of corn and soybeans (USDA, 2009), soybean processing (Hardy, 2009), and biofuel production (NBB, 2008; Hardy, 2009; RFA, 2009). Non-solar energy use for swine production in Iowa was last estimated as 36.2 MJ/kg live weight based on 1975 production statistics (Reid et al., 1980). Interest in non-solar energy use for all sectors of society is increasing due to rising energy prices, uncertainty about access to fossil fuel reserves, and growing consensus about the deleterious implications fossil fuel use has for global climate. As a leader in United States swine production and feed manufacture, a critical examination of non-solar energy use by modern Iowa swine production systems is over due.

Resource use by different types and scales of swine facilities differs (Lammers et al., 2009a; Lammers et al., 2009c). Conventional farrow-to-finish swine facilities in Iowa are mechanically ventilated buildings with liquid manure handling systems. Pigs are born in farrowing crates and at weaning are moved to a heated nursery facility. As pigs grow, they are often moved from nursery facilities to larger grow-finish buildings. Grow-finish buildings typically house 1,200 animals in pens of 30-60 animals. The entire floor space is slatted concrete. Gestation occurs in buildings similar to grow-finish buildings except pens are replaced with individual gestation stalls. Conventional housing for swine in Iowa and a hoop barn-based alternative have been detailed and examined (Lammers et al., 2009a; Lammers et al., 2009c). The hoop barn-based alternative uses similar farrowing and nursery facilities as the conventional system, but grow-finish pigs and gestating sows are housed in bedded hoop barns. Hoop barns in Iowa are 21.9×9.1 m Quonset™- shaped structures that have been previously described (Honeyman et al., 2001; Brumm et al., 2004; Harmon et al., 2004). Hoop barn sidewalls are approximately 1.5 m high and consist of wooden posts and sidewalls. Tubular steel arches are attached to the posts, forming a hooped roof. An ultraviolet light resistant, high-density polyethelyne tarp is pulled over the arches and fastened to the sidewalls. The floor is solid, usually concrete, with raised areas for eating and drinking. The rest of the floor is bedded with corn stalks or other plant materials. Buildings for grow-finish pigs are managed as a single pen with 180–200 animals per pen (Honeyman et al., 2001; Honeyman and Harmon, 2003; Lammers et al., 2009a; Lammers et al., 2009c). Gestating sows in hoop barns are managed in group pens with individual feeding stalls (Lammers, 2006; Lammers et al., 2008; Lammers et al., 2009a; Lammers et al., 2009c).

Constructing farrow-to-finish swine systems that use bedded hoop barns for grow-finish and gestation has been shown to require fewer construction resources and cost 17–30% less than systems that use conventional facilities (Lammers et al., 2009c). Operating hoop-based farrow-to-finish swine facilities is estimated to require 36% of the non-solar energy inputs of a conventional system (Lammers et al., 2009a). Crop sequence and diet formulation strategy also influences the non-solar energy use of swine production systems (Lammers et al., 2009b). The purpose of this paper is to examine non-solar energy use of different facility type × crop sequence × diet formulation strategies. Ecological impacts are also estimated based on non-solar energy use and nutrient cycling.

2. Methods

Process analysis methodology was used to calculate direct and indirect energy inputs based on physical material flows (Jones, 1989). Similar to previous assessments (Meul et al., 2007) a cradle-to-gate approach of LCA that included embodied energy one step before the farm was used. Consistent with process analysis methods, we did not include solar energy and human labor inputs (Jones, 1989). Managing pigs in hoop barns requires a different set of skills and proficiencies compared to managing pigs in conventional systems but labor is generally assumed to be similar for both types of housing systems.

2.1 Facilities

Previous examinations of constructing (Lammers et al., 2009c) and operating (Lammers et al., 2009a) farrow-to-finish swine systems were combined to estimate non-solar energy and greenhouse gas emissions associated with different types of pig facilities. Our analysis assumes the useful life of the conventional buildings is 15 years. The useful life of the hoop barns is also 15 years, but we include replacement of the thermoplastic tarp once within the 15 years in our report.

2.2 Diet formulation

Seven reference diets were the basis for calculating net energy (NE) and nutrient intake associated with production of one 136.0 kg market pig as previously described (Lammers et al., 2009b). Two general formulation strategies were considered in this analysis. The ratio of standardized ileal digestible (SID) lysine to NE was the basis for SIMPLE diet formulation. COMPLEX diet formulation began with first meeting the SID-to-NE requirement for threonine and tryptophan. The synthetic amino acids DL-methionine and L-lysine were then added as needed to provide adequate methionine and lysine. Because inclusion of the exongenous enzyme phytase has been shown to be energetically favorable (Lammers et al., 2009b) both diet strategies were formulated to include phytase.

Plant sources of P typically are not well utilized by pigs because swine do not produce adequate amounts of endogenous phytase (Crenshaw, 2001). Monocalcium phosphate (MCP) is a highly digestible in-organic source of P commonly used in pig diets. Inclusion of exogenous phytase makes plant P more available to pigs (Veum et al., 2006; Veum and Ellersieck, 2008; Emiola et al., 2009). It has been demonstrated that grain-soybean meal diets with exogenous phytase can be nutritionally adequate without any inorganic source of P in the diet (Veum et al., 2006; Veum and Ellersieck, 2008; Emiola et al., 2009). MCP was minimized in our diet formulations by excluding MCP unless the total phosphorus provided by the final diet (g total P: kJ NE) was not ≥ 100% of the available phosphorus presented by the reference diets.

2.3 Crop sequence × diet type

Three sets of diets were considered. The first diet type was a corn-soybean meal (Corn-Soy) diet typicaly fed in Iowa. The second diet type (Oat-Soy) is similar to the first except it includes oats. The third diet type (Co-product) is a Corn-Soy diet that included the biofuel co-products dried distillers' grains with solubles (DDGS) and crude glycerol. The Co-product diet type was formulated to include 25 and 40% DDGS for growing pigs and sows, respectively, and 10% crude glycerol for growing pigs. These inclusion rates correspond with recommended maximal inclusion rates for biofuel co-products in swine diets (Honeyman et al., 2007; Kerr et al., 2007).

Three previously described crop sequence scenarios were considered, they are a corn-soybean (C-S) sequence, a corn-soybean-corn-oat under seeded with alfalfa (C-S-C-O) sequence, and a corn-corn-soybean (C-C-S) sequence (Lammers et al., 2009b). The C-S sequence was assumed for the Corn-Soy diet type and the C-S-C-O sequence was assumed for the Oat-Soy diet type. The C-C-S sequence is paired with the Co-product diet type. Our previous model of crop production assumed that 100% of crop nutrients would be delivered by synthetic fertilizers and the crop sequence itself (Lammers et al., 2009b). For this analysis the crop production model included application of manure nutrients and reduced synthetic fertilizer use accordingly. Excretion of nitrogen (N) and phosphorus (P) from pigs fed different diets was estimated and then corrected for losses during storage and application.

2.3.1 Nutrient excretion from pigs

Total feed intake for each diet formulation was estimated and used to calculate intake of crude protein (CP), and total P as previously described (Lammers et al., 2009b). Based on previous reports, we estimated that if the hoop barn-based facilities were used, feed and nutrient intake of a given diet was 3.0% more than for conventional confinement facilities (Honeyman and Harmon, 2003; Lammers et al., 2009a). Excretion of N and P were calculated based on nutrient intake.

Nitrogen excretion was estimated based on results of a grow-finish feeding study (Canh et al., 1998). Pigs were fed diets containing 12.5–16.5% CP for 9 weeks with total collection of urine and feces (Canh et al., 1998). Based on the results of that study we estimate that for pigs fed 12–17% CP, N excretion can be calculated by the following equation:

Equation 1. Nitrogen excretion for growing pigs fed 12 − 17% crude protein

$$N_{ex} = 0.1369 \times CP_{in} - 15.154$$

Where

$$N_{ex} = \text{Nitrogen excretion, g}$$

$$CP_{in} = \text{Crude protein intake, g}$$

Phosphorus excretion was estimated based on results of 2 studies examining phytase in nursery (Veum and Ellersieck, 2008) and finishing (Veum et al., 2006) pigs. Both studies examined the efficacy of exogenous phytase by comparing P retention in pigs fed graded levels of exogenous phytase in diets formulated to be low in available P (Veum et al., 2006; Veum and Ellersieck, 2008). Both studies also included a positive control diet that was adequate in available P by inclusion of inorganic phosphorus sources (Veum et al., 2006; Veum and Ellersieck, 2008). The intake and excretion of P by pigs fed the negative and positive control diets in previous studies (Veum et al., 2006; Veum and Ellersieck, 2008) are the basis for the following equation used to predict phosphorus excretion by pigs in our assessment.

Equation 2. Phosphorus excretion by pigs

$$P_{ex} = 0.79 \times P_{in} - 1.0593$$

Where

$$P_{ex} = \text{Total phosphorus excreted, g}$$

$$P_{in} = \text{Total phosphorus intake, g}$$

Diet formulation affects energy density of the diets fed to pigs and pigs consume feed based on energy density of the diet. Because not all feed consumed is utilized by the pig, it is necessary to estimate relative differences in fecal mass when comparing different dietary strategies. Pigs fed Corn-Soy diets with synthetic amino acids were assumed to produce waste at rates found in tables used for developing manure management plans (ISU, 2003). For other diet formulations, for every 5% increase in feed intake over the baseline Corn-Soy scenario a 1% increase in waste volume was assumed.

2.3.2 Nutrient losses during storage and application

Loss of N from pig wastes during storage and application is a major concern (ISU, 2003; IPCC, 2006; Wathes and Whittemore, 2006). Losses from different types of storage systems vary (Arogo et al., 2003; Nicks et al., 2004; Phillippe et al., 2006; Phillippe et al., 2007). Previous examinations of nitrogen loss from swine manure storage units have focused on liquid manure systems or deep-litter systems that use sawdust. Only 1 study has examined the characteristics of cornstalk bedding packs in hoop barns (Tiquia et al., 2002). Using a mass balance approach, N losses of 35–45% were reported. European researchers have reported N losses of only 28% from deep-litter pens when using straw (Nicks et al., 2004). Others report N losses of up to 75% from deep-litter pens using straw bedding (Phillippe et al., 2006). No published studies have specifically examined N loss from liquid manure stored in deep pits compared to N loss from bedded hoop barns. For our analysis we assume nitrogen losses of 25% from liquid manure storage and 50% from bedded hoop barns (IPCC, 2006).

Liquid manure is often direct injected into cropland. Our model assumes liquid manure is directly injected into cropland after removal from storage and that 98% of the N in the stored manure is delivered to crop fields and that it 100% is available to crops in the year of application (ISU, 2003). For every 100 kg N excreted by pigs and handled as liquid manure, our analysis assumes 73.5 kg of N is available to crops with 25 kg N lost during storage and 1.5 kg lost during application.

Manure and bedding from hoop barns is often composted prior to application. The ratio of C:N in the composting material, moisture content, and frequency of turning have all been shown to influence reduction of material mass, total losses of N , and type of N emission from composting pig manure (Huang et al., 2001; Tiquia et al., 2002; Huang et al., 2004). Our analysis assumes no turning of compost and that a 40% reduction in material mass occurs (Tiquia et al., 2002). Our analysis assumes that the 50% N loss reported previously includes all N loss during storage and composting (IPCC, 2006). Our analysis assumes 0% loss of N from stable compost that is applied and incorporated to crop fields and that 60% of the delivered N is available to plants during the year of application with the remaining 40% available to plants in the following year (Shaffer, 2001). For every 100 kg of N excreted by pigs housed in bedded hoop barns, our analysis assumes 50 kg of N is available to crops over a 2-year period.

Phosphorus does not volatilize and under most manure storage and handling scenarios most of the excreted P is delivered to crop fields (Fulhage and Hoehne, 2001). Our analysis assumes 100% of the excreted P is delivered to crop fields and is available for plant growth in the year of application. We also assume that cropland has a P-index of 2–5 which allows N-based manure management but prohibits P application rates exceeding two times the P removal rates of the crop schedule (USDA-NRCS, 2004; IADNR, 2006).

2.3.2.1 Land application of manure slurry or compost

Our model assumes swine waste is returned to cropland that was used to grow crops fed to pigs. Application rates of swine manure were based on nutrient removal rates by the crops with application of synthetic fertilizers reduced accordingly (Lammers et al., 2009b). Concentration of nutrients in swine manure slurry or compost were calculated for liquid manure systems and the bedded hoop barns. For liquid pig manure, the mass of N and P after taking into account storage and application losses were divided by the calculated slurry volume. Non-solar energy use for transporting and injecting liquid pig manure into cropland is reported as 20.8 kJ/L (Wiens et al., 2008). Application rate was calculated based on manure slurry nutrient concentration and nutrient removal rates by crops. We assume non-solar energy use of 20.8 kJ/L of liquid swine manure applied.

For swine manure compost, the mass of N and P after taking into account storage and composting losses were divided by the mass of the finished compost. Application rate was calculated based on nutrient concentration of the compost and nutrient removal rates by crops. It was assumed that compost would be loaded onto a trailer with a capacity of 22,000 kg and hauled an average of 3.2 km with an average fuel efficiency of 3.0 km/L. Energy density of diesel fuel is assumed to be 38.46 MJ/L. Thus transportation energy cost of delivering compost to fields was calculated as 1.9 kJ/kg. Energy use for spreading the compost across the field was estimated based on reported diesel fuel use for field operations (Downs and Hansen, 1998; Hanna, 2001).

Use of diesel fuel for transporting, injecting or spreading liquid swine manure or compost results in emission of greenhouse gases. The 100-yr global warming potential of diesel fuel consumption is reported as 63.52 g CO2 equivalents/MJ non-solar energy as diesel fuel (IPCC, 2006). Diesel fuel consumption for manure handling was totaled and used to calculated greenhouse gas emissions associated with non-solar energy use for manure handling for each diet × housing comparison.

2.5 Reporting

The baseline system—conventional confinement housing, pigs fed a COMPLEX Corn-Soy diet, C-S cropping sequence—was first modeled and summarized. Selected combinations of facility type × diet formulation × crop sequence scenarios were also examined and compared. For each facility type × diet formulation × crop sequence scenario examined the land area, non-solar energy use, and 100-yr GWP for the entire pig production system was calculated and divided by the number of 136.0 kg market pigs produced. Not all grains, oilseeds, and biomass produced within a crop sequence are necessarily consumed by pigs. Crop products not consumed by pigs are assumed to be exported from the farm. Exported crop production for each housing × diet formulation × crop sequence scenario were calculated and reported. All scenarios are designed to provide adequate corn and oats. As needed soybean meal is imported to the farm. Imports and exports of crop products were totaled and compared for each facility type × diet formulation × crop sequence scenario considered.

3. Results

3.1 Baseline scenario

Table 1 presents the baseline scenario for pig production in Iowa. In the baseline scenario each market pig is estimated to require 967.6 MJ non-solar energy and result in 79.8 kg CO_2 equivalents. Approximately 60% of the non-solar energy use for pig production is associated with growing and processing feed ingredients. Fifty percent of the non-solar energy use is due to cultivation of crops. Feed ingredient manufacture and processing of feed accounts for just over 9% of total energy. Although 19% of the non-solar energy use results from facility operation, 28% of the 100-yr GWP results from that activity. Nearly 30% of non-solar energy use is associated with construction and operation of facilities, and 37% of the 100-yr GWP associated with pig production can be attributed to facility construction and operation in the Corn-Soy baseline scenario. The baseline scenario assumes a C-S cropping sequence and results in export of 20.9 kg soybean meal and 17.3 kg soy oil per market pig sold. The total crop land area needed to produce feed grown on farm is 535 m^2/market pig or a total of 834.6 hectares for the 15,600 pig system.

Table 2 details two additional crop sequence and diet type scenarios for the conventional confinement facilities. The SIMPLE Oat-Soy diet formulation does not include L-lysine and requires almost 25% less energy for processing feed ingredients compared to the baseline scenario. However energy used to cultivate crop is 35% more for the SIMPLE

Oat-Soy option compared to the baseline. Including synthetic amino acids increases the processing energy required for pig diets and decreases the CP content of the feed and ultimately the amount of N excreted by the pig. Removing synthetic amino acids from diets should increase N excretion, increasing N delivery to fields, and reduce the need for synthetic N fertilizers. However the benefits of feeding higher CP to pigs and reducing application of N fertilizers to cropland is not energetically favorable in the conventional systems compared.

Cultivation energy for the COMPLEX Co-product diet formulation was less than any other scenario, however the processing energy is 5–7 times greater. This is because of the way DDGS and crude glycerol were assessed. Our analysis assumes DDGS and crude glycerol are imported to the farm and that cultivation of the corn and soybeans required to produce those biofuel co-products are attributed to the processing energy of those feed ingredients. The different crop sequence × diet formulations result in differing crop surpluses. The baseline scenario assumes a C-S sequence and results in export of 20.9 kg soybean meal and 17.3 kg soy oil per market pig respectively. The SIMPLE Oat-Soy scenario assumes a C-S-C-O sequence and results in export of 121.3 kg corn grain, and 10.43 kg soy oil/market pig but requires the importing of 29.47 kg of soybean meal/market pig. The COMPLEX Co-product scenarios with a C-C-S sequence imports 19.30 kg soybean meal and exports 6.78 kg soy oil/market pig.

A hoop-based pig production system requires less non-solar energy for operation of facilities, but also requires more feed. Because liquid pig manure from conventional facilities and swine manure compost from hoop barns have different release rates of crop available nutrients, different cropping sequences may be more effective in a hoop barn-based system than in the conventional confinement system. Table 3 details three diet formulation ×

cropping sequence scenarios for farrow-to-finish swine production using hoop barns for gestation and grow-finish. Feeding pigs housed in hoop barns a COMPLEX Corn-Soy diet from C-S cropping sequence require 939.8 MJ non-solar energy and results in 79.8 kg CO_2 equivalents per market pig sold. This is 3% less than the non-solar energy use associated with the same diet × crop sequence scenario when pigs are housed in conventional confinement. The hoop barn system results in 12% less 100-yr global warming potential compared to the conventional system. The hoop barn-based system's advantage is in reduced operating energy requirements and manure handling. Injecting liquid pig manure using an umbilical cord systems requires a 20.8 MJ/L (Wiens et al., 2008). Loading, hauling, and surface spreading finished swine manure compost requires less energy per unit of fertility delivered to crop fields. Operating the hoop barn-based complex requires 39% less non-solar energy than a conventional confinement system. This dramatic difference more than offsets the additional energy needed to grow feedstuffs and process feed ingredients in the hoop barn-based system.

A SIMPLE Oat-Soy diet fed to pigs housed in hoop barns requires 19% more total non-solar energy input compared to the baseline conventional system. Feeding a SIMPLE Oat-Soy diet to pigs in hoop barns requires similar energy as feeding the same diet to pigs housed in conventional systems, once again because of the effects of different manure handling systems and facility operating requirements. The COMPLEX Co-product diet strategy required the most non-solar energy input in both the hoop barn-based and conventional confinement systems. In terms of non-solar energy use per market pig produced feeding biofuel co-products to pigs may not be the optimal use for those co-products, although comparative pricing of various feed ingredients at different locations may make feeding biofuel co-products economical for individual producers.

Although the main product of swine production systems is obviously pigs, not all crop products grown within a particular sequence are necessarily consumed by pigs. Table 4 summarizes the mass of crop products potentially exported from each facility × diet type × formulation strategy. Because the focus of this examination is energy, the NE value of the exported feedstuffs when fed to pigs is totaled. We also present the NE of any feedstuffs that need to be imported. From those two values a net NE can be calculated. The C-S-C-O sequences produce an abundance of corn and this results in those systems exporting NE as feedstuffs from the farm despite the need to import soybean meal. All sequences examined export soy oil, which ultimately leads to a positive balance of exported - imported feedstuffs in terms of NE for pigs.

For all scenarios considered, growing and processing swine feed was the largest contributors to total non-solar energy and 100-yr global warming potential associated production of one 136.0 kg market pig in Iowa farrow-to-finish swine systems. The energy and 100-yr global warming potential of facility construction and operation is not inconsequential and should be included in future assessments of swine production systems. As expected the impact of non-solar energy use required to construct and operate different swine production systems influences the total balance of the system. Despite using more non-solar energy for production and delivery of feed, farrow-to-finish systems using hoop barns for grow-finish pigs and gestating sows use similar or less non-solar energy as comparable conventional systems.

Current reports from Europe of non-solar energy use for pig production range from 5.3–23.5 MJ/kg live weight (Basset-Mens and van der Werf, 2005; Ericksson et al., 2005; Williams et al., 2006). Previous reports have been conducted in Europe and have likely assumed very different crop production and feed processing scenarios than what we have presented. Others have not included facility operation, focusing exclusively on feeding strategies. With nearly 30% of the non-solar energy use required to produce a pig resulting from facility construction and operation reports that do not include this aspect of pig production are incomplete. We estimate that raising pigs in conventional confinement systems operating in Iowa uses 7.1 MJ non-solar energy per kg of live weight pig. The alternative system using hoop barns for grow-finish pigs and gestating sows may reduce the non-solar energy use by 3% to 6.9 MJ/kg of live weight. Hoop barn-based swine production systems can be managed to use similar or less resources than conventional systems. Although the conventional system did not develop within a vacuum, as we strive to optimally allocate non-solar energy reserves and reduce the global warming potential of pig production, support for alternative systems such as hoop barns is warranted.

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Table 1. Assessment of non-solar energy and 100-yr global warming potential associated with farrow-to-finish pig production in Iowa in the baseline system[1].

	Non-solar Energy, MJ/pig	100-yr GWP kg CO_2 equivalents/pig
Facility construction	87.0	6.7
Facility operation	185.4	22.7
Cultivation of crops	512.6	38.1
Processing of feed	99.5	7.0
Manure application	83.1	5.3
Total	967.6	79.8

[1] Conventional confinement facilities scaled to produce 15,600 market pigs annually. Requires 535 m^2 cropland/market pig and results in surplus production of 20.9 kg soybean meal and 17.3 kg soy oil.

Table 2. Alternative crop sequences and diet formulation strategies for Iowa farrow-to-finish systems using conventional confinement scaled to produce 15,600 market pigs annually.

	Non-solar energy, MJ/pig	100-yr GWP, kg CO_2 equivalents/pig	Non-solar energy, MJ/pig	100-yr GWP, kg CO_2 equivalents/pig
Building construction	87.0	6.7	87.0	6.7
Building operation	185.4	22.7	185.4	22.7
Cultivation of crops	694.2	51.4	425.1	31.0
Processing of ingredients	74.9	6.8	561.6	20.0
Manure application	84.1	5.3	84.3	5.4
Total	1,125.6	92.9	1,343.4	85.8
System Characteristics				
Crop sequence	C-S-C-O		C-C-S	
Diet type	Simple Oat-Soy		Complex Co-product	
On-farm feed production area	629.2 m^2/pig		306.8 m^2/pig	
Off-farm feed production area	96.9 m^2/pig		277.6 m^2/pig	
Imported soybean meal	29.47 kg/pig		19.30 kg/pig	
Surplus corn grain	121.30 kg/pig		0	
Surplus soy oil	10.43 kg/pig		6.78 kg/pig	

Table 3. Assessment of non-solar energy and 100-yr global warming potential associated with Iowa farrow-to-finish pig production systems using bedded hoop barns for gestating sows and grow-finish pigs.

	Non-solar energy, MJ/pig	100-yr GWP, kg CO_2 equivalents/pig	Non-solar energy, MJ/pig	100-yr GWP, kg CO_2 equivalents/pig	Non-solar energy, MJ/pig	100-yr GWP, kg CO_2 equivalents/pig
Facility construction	73.2	5.4	73.2	5.4	73.2	5.4
Facility operation	113.9	9.9	113.9	9.9	113.9	9.9
Cultivation of crops	622.7	45.8	854.6	62.5	543.3	39.1
Processing of feed	102.5	7.2	79.5	7.2	578.4	20.6
Manure application	20.6	1.3	20.9	1.3	20.8	1.3
Harvesting bedding	6.9	0.6	6.9	0.6	6.9	0.6
Total	939.8	70.2	1,149.1	86.9	1,336.5	76.9
System Characteristics						
Crop sequence	C-S		C-S-C-O		C-C-S	
Diet type	COMPLEX Corn-Soy		SIMPLE Oat-Soy		COMPLES Co-products	
On farm feed production area	551.0 m^2		667.6 m^2		316.2 m^2	
Off-farm production area	0		102.8 m^2		279.5 m^2	
Imported soybean meal	0		31.26 kg/pig		19.87 kg/pig	
Surplus corn grain	0		128.72 kg/pig		0	
Surplus soy oil	17.8 kg/pig		11.7 kg/pig		7.0 kg/pig	
Surplus soybean meal	21.53 kg/pig		0		0	

Table 4. Feedstuff surpluses and deficits associated with production of one 136.0 kg market pig under selected facility × diet type × crop sequence scenarios.

Facility	Conventional Confinement			Hoop Barn-Based		
Diet type	Corn-Soy	Oat-Soy	Co-product	Corn-Soy	Oat-Soy	Co-product
Crop Sequence	C-S	C-S-C-O	C-C-S	C-S	C-S-C-O	C-C-S
Corn grain, kg	0	121.3	0	0	128.7	0
Soy oil, kg	17.3	10.4	6.8	17.8	11.7	7.0
Soybean meal, kg	20.9	-29.5	-19.0	21.5	-31.3	-19.9
NE exported[1], MJ	691.1	1,657.2	202.0	711.3	1788.6	208.6
NE imported[1], MJ	0	247.6	159.9	0	180.9	166.9
Balance, MJ	691.1	1,409.6	42.1	711.3	1,607.7	41.7

[1] Based on Sauvant et al. (2004)

CHAPTER 9. GENERAL CONCLUSIONS

Assessing non-solar energy use and ecological impacts of swine production systems is a complex process that must take into consideration feed choice and diet formulation strategy, pig growth and performance assumptions, as well as facility type and management. The variability in Iowa swine farms is decreasing, still there is sufficient diversity in existing production systems that drawing firm conclusions about the advantages of one system over another is difficult if not impossible. Previous energy assessments of pork production have focused on European conditions and our work demonstrates that results and recommendations from Europe should be interpreted by U. S. swine producers and policy makers with caution. Differences in feed ingredient mix, crop production systems, and management strategies between Iowa and Europe support continued assessment of North American swine production systems.

The choice in facility type dramatically effects the amount of construction resources and total cost of building swine production facilities. A system that uses bedded hoop barns for gestating sows and grow-finish pigs requires approximately 15% less concrete and lumber and 30% less steel than a system using conventional confinement facilities. The hoop barn-based system requires 30% more land area for its building site, but building site costs are a very small portion of the total cost of building swine facilities. Total construction costs for a hoop barn-based system is 17% less than a conventional system. Increasing the scale of pig production from 5,200 to 15,600 market pigs annually reduces construction cost per pig by 25% in conventional systems. The same increase in scale reduces construction cost per pig space by only 14% in a hoop barn-based system. The construction cost/pig space of a 5,200 head farrow-to-finish system using hoop barns for gestating sows and grow-finish pigs is less than the construction cost/pig space of a conventional 15,600 head farrow-to-finish system. Systems that use hoop barns may be more scale neutral than conventional systems.

Nearly 30% of the non-solar energy use of a conventional pig production system is associated with constructing and operating pig facilities. Mechanically ventilated pig facilities modify the pig's thermal environment through the use of liquefied petroleum gas and electricity. Although heating and ventilating pig barns allows managers to maintain temperatures within the pig's thermal comfort zone this management approach requires large amounts of energy inputs. Hoop barns modify pig environment through the use of bedding and increased feed consumption. These inputs also require energy but are generally considered renewable resources. Currently conventional systems rely heavily on direct use of fossil fuels to maintain pig comfort. Both conventional and hoop barn-based systems are currently dependent on fossil fuels to operate, however a hoop barn-based system requires approximately two thirds the non-solar energy inputs that a conventional system needs to function. Greenhouse gas emissions from agriculture are increasingly being scrutinized. By reducing non-solar energy inputs required to operate a system, greenhouse gas emissions associated with pig production can also be reduced. Operating a hoop barn-based system reduces greenhouse gas emission associated with pig facilities by more than 50% compared to the conventional system.

Feed is the largest single input into a pig production system, both in terms of cost and non-solar energy use. This is the reason why most assessments of pork production focus heavily on feedstuff choice and diet strategies. The non-solar energy and resulting global warming potential associated with growing and processing feed ingredients commonly used in Iowa has not been previously reported. Although far from complete the inventory of 13 feedstuffs included in this dissertation is a starting point.

Biofuel production is increasing and this results in production of co-products that may be fed to pigs. Crude glycerol is a co-product of biodiesel production. This relatively unexamined feedstuff is an excellent source of energy for pigs. The apparent metabolizable energy of the crude glycerol we examined is 3,207 ± 10 kcal/kg. Biodiesel production occurs at many different processing plants each with their own standard operating procedures and expectations. This results in variability of the co-product crude glycerol. Responsible nutritionists must consider this when formulating diets to include crude glycerol just as they would for any other feed ingredient. We have demonstrated that pigs can be fed up to 10% crude glycerol from wean to finish without influencing average daily gain, average daily feed intake, or the gain to feed ratio. Crude glycerol supplementation did not affect carcass or pork quality, although fatty acid profile of longissimus muscle lipid was slightly altered. Methanol is a trace contaminant found in crude glycerol from biodiesel production that can be detrimental to pigs. However we found no evidence of methanol toxicity in pigs fed up to 10% crude glycerol during a 138-d feeding trial.

Including biofuel co-products in the diet of pigs may be economical and is an excellent way to harvest an available resource. However non-solar energy use for growing, processing, and delivering swine diets including dried distiller's grains and crude glycerol requires greater than 33% more non-solar energy compared to a typical corn-soybean meal diet. Feeding phytase reduces the need for inorganic phosphorus in pig diets and dramatically reduces the non-solar energy use of pig diet production. Synthetic amino acids when fed to pigs reduce nitrogen excretion due to more precise matching of amino acid delivery with pig needs, but requires more non-solar energy inputs than meeting amino acid needs by feeding soybean meal. Replacing soybean meal with full-fat soybeans allows producers to process a greater percentage of total feed on-farm. Replacing soybean meal with full-fat soybeans requires more non-solar energy for pig feed production. Locations that require long distance transport of soybean meal may benefit from local processing of alternative protein sources, but this is not the situation for Iowa.With soybean meal processing plants dispersed throughout the state there is no energetic advantage to replacing soybean meal with full-fat soybeans.

The “standard” pig production system is Iowa is conventional confinement with a diet consisting of corn and soybean meal. Typical crop sequence is corn-soybean and swine diets include synthetic amino acids and the exogenous enzyme phytase. This same crop sequence × diet formulation pairing can be incorporated into a system using hoop barns for gestation and grow-finish and results in a reduction of non-solar energy use and global climate altering emissions. There are benefits to more complex crop sequences. However those sequences are not as well suited as a corn-soybean sequence in terms of producing swine feedstuffs. A corn soybean sequence delivers adequate nutrition to pigs and requires the least non-solar energy input.

The total non-solar energy input associated with one 136 kg pig produced in a conventional farrow-to-finish system in Iowa and fed a typical corn-soybean meal diet that included synthetic lysine and exogenous phytase is 967.6 MJ. Consuming this non-solar energy results in emission of 79.8 kg of CO_2 equivalents. Alternatively producing the same pig in a system using hoop barns for gestating sows and grow-finish pigs requires 939.8 MJ/pig and results in emission of 70.2 kg CO2 equivalents, a reduction of 3 and 12%

respectively. Hoop barn-based swine production systems can be managed to use similar or less resources than conventional confinement systems. As we strive to optimally allocate non-solar energy reserves and other limited resources, support for examining and improving alternative systems is warranted.

APPENDIX 1: CALCULATING ENERGY USE FOR THERMAL CONTROL OF GROW-FINISH FACILITIES WITHIN A FARROW-TO-FINISH SYSTEM PRODUCING 15,600 MARKET PIGS ANNUALLY

Step 1. *Divide exterior temperature data between hours with pigs and hours with no pigs in building.*

Table 1 summarizes historic temperature date for the location modeled as well as the division of time between when pigs are housed in the building and when the building is empty. Temperature data is for Mason City, IA, 43.1°N, 93.2°W for the years 1961–1990 (Kjelgaard, 2001). The division of time is based on pig flow assumptions detailed previously (Lammers et al., 2009).

Step 2. *Calculate the balance point temperature of the building.*

The balance point temperature is the exterior temperature at which the building is in thermal balance—interior temperature remains constant without additional heat inputs or losses. The balance point temperature is calculated based on the following equation presented by MWPS publications (MWPS, 1987, 1990a, b):

$$t_b = t_i - (HP \div (A_T/R_T + 1.1 \times cfm_{MIN} \times Head) \qquad \text{(Equation 1)}$$

Where

t_b = Balance point temperature, °F
t_i = Inside temperature, °F
HP = Heat production by pigs, Btu/hr
A_T/R_T = The sum of all area/resistance ratios of the building, Btu/hr • °F
or $(A_S/R_S) + (A_P/R_P)$
1.1 = Conversion factor
cfm_{MIN} = Minimum ventilation rate, $ft^3 \times min^{-1} \times pig^{-1}$
Head = Number of pigs in building

Balance point temperature and long-term climate data can be used to estimate the number of hours a particular facility will need additional heat added or removed during a year. The number of hours that the exterior temperature is less then the balance point temperature is the number of hours in a year that additional heat must be added. Alternatively the number of hours that the exterior temperature is greater than the balance point temperature is the number of hours in a year that additional heat removal strategies are needed. The grow-finish building houses 1,200 pigs, each pig has a body weight of 85.3 kg and produces 531.4 kJ of sensible heat. Assuming a minimum room temperature of 15.5°C and minimum ventilation rate of 283 L × min^{-1} × hd^{-1}, the balance temperature is -9.2°C.

Step 3. *Determine number of hours that heat will be need to be added to the building and the least square mean exterior temperature for that time frame.*

The balance point temperature for the grow-finish building example is -9.2°C. A sub-set of temperature × time data points from table 1 can now be identified. All temperature × time data points ≤ -9.2 °C are included in the subset and all temperature × time data points > -9.2°C are excluded. Table 2 Summarizes the number of hours pigs occupy the building at temperatures ≤ -9.2°C. This information can be used to calculate the least square mean temperature for the 1,063.2 hr when exterior temperatures are ≤ -9.2°C. The exterior temperature is calculated as -16.3°C for the 1,063.2 hr when additional heat is needed.

Step 4. *Calculate heat inputs required.*

The thermal balance of a pig building is calculated following the general equation:

$$\text{Thermal balance (Btu/hr)} = H_{in} - H_{out} \qquad \text{(Equation 2)}$$

Where

H_{in} = Sensible heat production by pigs, Btu/hr

H_{out}= Heat loss from building surfaces, Btu/hr + Heat loss from ventilation, Btu/hr

If the thermal balance is negative, additional heat must be added to the building to maintain interior temperature at a given set-point. If thermal balance is positive, additional heat must be removed from the building to prevent interior temperature from increasing.

Heat production by pigs is calculated using equations based on Pedersen (2002) and Brown-Brandl et al. (2004). Heat production by growing pigs is calculated using the appropriate equation based on body weight:

Total heat production by pigs $\leq$ 10 kg:

$$HP = 4.3 \times BW^{0.15} \times BW \times Head \times 3.41214 \qquad \text{(Equation 3a)}$$

Total heat production by pigs > 10 kg

$$HP = 14.11 \times BW^{-0.38} \times BW \times Head \times 3.41214 \qquad \text{(Equation 3b)}$$

Where

HP = Heat production, Btu/hr
BW = Body weight, kg
Head = Number of pigs in building
3.41214 = Conversion factor W to Btu/hr

Heat production by adult pigs is influenced by body weight as well as production phase. Heat production by gestating sows or lactating sows with litters is calculated using one of the following production phase specific equations:

Total heat production by gestating sows

$$HP = (4.85 \times BW^{0.75} + 2 \times 10^{-0.5} \times DP^{3} + 76 \times 0.18) \times Head \times 3.41214 \qquad \text{(Equation 4a)}$$

Total heat production by lactating sows

$$HP = (4.85 \times BW^{0.75} + 28 \times 6 + 76 \times 0.18) \times Head \times 3.41214 \qquad \text{(Equation 4b)}$$

Where

HP = Heat production, Btu/hr
BW = Body weight, kg
DP = Days of pregnancy, d
Head = Number of sows in building
3.41214 = Conversion factor W to Btu/hr

The amount of heat produced as sensible heat is then calculated as a temperature dependent percentage of the total heat production based on Pedersen (2002) and Brown-Brandl et al. (2004).

Heat loss from the building is calculated using equations presented by MWPS publications (MWPS, 1987, 1990a, b). Heat loss from each building surface is calculated using the general equation:

$$BSL = (A_S/R_S) \times (t_i\text{-}t_o) \qquad \text{(Equation 5a)}$$

Where

BSL = Heat loss through a surface, Btu/hr
A_S = Surface area, ft^2
R_S = Total resistance of the surface to heat flow, °F•ft^2•hr/Btu
t_i = Inside temperature, °F
t_o = Outside temperature, °F

Heat loss through the floor perimeter is calculated using the following equation:

$$HLFP = (A_P/R_P) \times (t_i\text{-}t_o) \qquad \text{(Equation 5b)}$$

Where

$HLFP$ = Heat loss through floor perimeter, Btu/hr
A_P = Building perimeter, ft
R_P = Resistance of perimeter to heat flow, °F•ft•hr/Btu
t_i = Inside temperature, °F
t_o = Outside temperature, °F

The losses from each surface are added together to calculate the total heat loss from surfaces of the building. Heat loss from ventilation necessary to maintain air quality is calculated using the following equation:

$$HLV_{MIN} = 1.1 \times cfm_{MIN} \times (t_i\text{-}t_o) \times Head \qquad \text{(Equation 6)}$$

Where

HLV_{MIN} = Heat loss from minimum ventilation, Btu/hr
1.1 = Conversion factor
cfm_{MIN} = Minimum ventilation rate, $ft^3 \times min^{-1} \times pig^{-1}$
t_i = Inside temperature, °F
t_o = Outside temperature, °F
Head = Number of pigs in building

Table 3 summarizes the value of key variables in equations 1-6 for the grow-finish building example. By manipulating variables presented in table 3 and equations 1-6 we find that 194.3 MJ/hr additional heat must be added to the building in order to maintain an interior temperature of 15.5°C when exterior temperatures are -16.3°C. Calculating the additional heat input is then simply a matter of multiplying heat input/hr by the number of hours modeled. In this example:

194.3 MJ/hr × 1,063.2 hr = 206.6 GJ/building

Assuming a heater efficiency of 98% approximately 210.8 GJ of heat must be added to the described grow-finish building annually when pigs are housed in the building.

Steps 2–4 are then repeated for when no pigs are housed in the building. When no pigs are present, heat production is zero, ventilation is reduced to 650 L/min for the entire building and interior temperature is maintained at 10°C. This results in a balance temperature of 10°C. A second sub-set of temperature × time data points was then drawn from table 1 and is summarized as table 4. The least square mean temperature for hours that require additional heat inputs when no pigs are present is -3.1°C. Table 5 summarizes the value of key variables in equations 1-6 for the empty grow-finish building example. By manipulating variables presented in table 5 and equations 1-6 we find that 34.3 MJ/hr additional heat must be added to the building in order to maintain an interior temperature of 10°C when exterior temperatures are -3.1°C. Calculating the additional heat input is then simply a matter of multiplying heat input/hr by the number of hours modeled. In this example:

34.3 MJ/hr × 47.8 hr = 1.6 GJ/building

Assuming a heater efficiency of 98%, 1.7 GJ of heat must be added to the described grow-finish building annually when the building is empty. The total heat required by this grow-finish building for 1 year is thus 212.5 GJ. With 4 grow-finish buildings in the system producing 15,600 market pigs annually a total of 850 GJ of heat input is needed for thermal climate control of grow-finish buildings.

Step 5. *Calculate energy used for maintaining air quality*

Pigs are housed in the grow-finish building 8,672.4 hr/yr. The ventilation rate needed to maintain air quality (minimum ventilation) for the 85.3 kg pig in our model is 283 L $\times$ min^{-1} $\times$ head^{-1}. With a fan efficiency of 339.8 L $\times$ min^{-1} $\times$ W^{-1} operating the minimal ventilation fans requires 999.4 W. Thus a total of 8,667.2 kW•hr or 31.2 GJ of electricity is required to operate minimal ventilation fans when pigs are housed in one grow-finish building. Therefore a total of 124.8 GJ electricity is needed to maintain air quality inside 4 grow-finish buildings in the 15,600 market pigs/year system when pigs are present.

The grow-finish building is empty of pigs for 87.6 hours. When the barn has no pigs in it, the minimal ventilation rate is 650 L/min. Fan efficiency is 339.8 L $\times$ min^{-1} $\times$ W^{-1}, thus maintaining air quality when no pigs are present requires a total of 0.2 kW•hr or 0.7 MJ per building. The total electricity needed for maintaining minimal air quality in the 4 grow-finish buildings for the 15,600 market pig/year system is slightly more than 124.8 GJ/year.

Step 6. *Calculate the energy used to reduce interior temperature of barns*

If exterior temperature is greater than the balance point temperature but less than the maximum allowable interior temperature, increasing the ventilation rate will remove heat from the building and maintain interior temperatures within the accepted range. Additional ventilation to remove heat from a building is calculated using the following equation from MWPS publications (MWPS, 1987, 1990a, b):

$$cfm_{ADD} = (DHL \div [1.1 \times (t_i - t_o)]) \div Head \qquad \text{(Equation 7)}$$

Where

cfm_{ADD} = Additional ventilation rate, $ft^3 \times min^{-1} \times hd^{-1}$
DHL = Desired heat loss, Btu/hr
1.1 = Conversion factor
t_i = Inside temperature, °F
t_o = Outside temperature, °F
Head = Number of pigs in building

In situations where the exterior temperature is greater then both the balance point temperature and the interior temperature of the building, interior temperature will increase unless additional cooling tactics are used. Circulating fans, sprinklers, water drippers, evaporative cooling systems, and zone cooling are examples of additional cooling strategies. These tactics require energy but are beyond the scope of this model. When the exterior temperature is greater than the interior temperature, energy use is estimated based on hot weather ventilation rates presented by MWPS publications (MWPS, 1987, 1990a, b).

Tables 5 and 6 summarizes the different temperature × hour data used to calculate cooling of pig buildings with and without pig present respectively. Equations 1-7 and fan efficiency assumptions can then be manipulated to calculate the energy used for cooling pigs. Table 8 summarizes energy use for thermal control of 1 grow-finish building in a farrow-to-finish swine production system producing 15,600 market pigs annually.

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Table 1. Historic exterior temperature for Mason City, IA (43.1°N, 93.2°W)[a]

Temperature, °C	Total time, hours/year	Pigs in barn, hour/yr	Barn empty, hr/yr
33.6	20	19.8	0.2
30.8	75	74.3	0.8
28.1	258	255.4	2.6
25.3	429	424.7	4.3
22.5	526	520.7	5.3
19.7	567	561.3	5.7
16.9	941	931.6	9.4
14.2	603	597.0	6.0
11.4	565	559.4	5.7
8.6	519	513.8	5.2
5.8	437	432.6	4.4
3.1	744	736.6	7.4
0.3	616	609.8	6.2
-2.5	550	544.5	5.5
-5.3	454	449.5	4.5
-8.1	382	378.2	3.8
-10.8	327	323.7	3.3
-13.6	228	225.7	2.3
-16.4	159	157.4	1.6
-19.2	84	83.2	0.8
-21.9	127	125.7	1.3
-24.7	90	89.1	0.9
-27.5	46	45.5	0.5
-30.3	10	9.9	0.1
-33.1	3	3.0	0.0
Total	8,760	8672.4	87.6

[a] 1961–1990 based on (Kjelgaard, 2001)

Table 2. Hours and least square mean temperature below balance temperature for grow-finish building example when pigs are inside building.

Temperature, °C	Hours with pigs, hr	Temp. × Hour
-10.8	323.7	-3,496.0
-13.6	225.7	-3,069.5
-16.4	157.4	-2,581.4
-19.2	83.2	-1,597.4
-21.9	125.7	-2,752.8
-24.7	89.1	-2,200.8
-27.5	45.5	-1,251.3
-30.3	9.9	-300.0
-33.1	3.0	-99.3
Total	1,063.2	-17,348.5
LS Mean Temperature, °C		-16.3

Table 3. Values of key variables needed to calculate energy use for heating example grow-finish buildings when pigs are present.

Variable	Value
Pigs	1,200 hd
Body weight	85.3 kg
Heat production	531.4 kJ/hd
Minimum ventilation	283 L × min^{-1} × hd^{-1}
A_T/R_T	4.43 MJ/hr-°C
Exterior temperature	-16.3°C
Interior temperature	15.5°C

Table 4. Hours and least square mean temperature below balance temperature for grow-finish building example when pigs not in building.

Temperature, °C	Hours With no pigs, hr	Temp. × Hour
8.6	5.2	44.7
5.8	4.4	25.5
3.1	7.4	22.9
0.3	6.2	1.9
-2.5	5.5	-13.8
-5.3	4.5	-23.9
-8.1	3.8	-30.8
-10.8	3.3	-35.6
-13.6	2.3	-31.3
-16.4	1.6	-26.2
-19.2	0.8	-15.4
-21.9	1.3	-28.5
-24.7	0.9	-22.2
-27.5	0.5	-13.8
-30.3	0.1	-3.0
-33.1	0.0	0
Total	47.8	-149.5
LS Mean Temperature, °C		-3.1

Table 5. Values of key variables needed to calculate energy use for heating example grow-finish building with no pigs present.

Variable	Value
Pigs	0
Heat production	0
Minimum ventilation	650 L × min^{-1}
A_T/R_T	4.43 MJ/hr-°C
Exterior temperature	-3.1°C
Interior temperature	10.0°C

Table 6. Hours and least square mean temperature for different cooling scenarios with pigs in barn

Ventilation Rate Increased to Maintain Room Temperature		
Temperature, °C	Hours with pigs in barn/yr	Temperature × hour
22.5	520.7	11,715.8
19.7	561.3	11,057.6
16.9	931.6	15,744.0
14.2	597.0	8,477.4
11.4	559.4	6,377.2
8.6	513.8	4,418.7
5.8	432.6	2,509.1
3.1	736.6	2,283.5
0.3	609.8	182.9
-2.5	544.5	-1,361.3
-5.3	449.5	-2,382.4
-8.1	378.2	-3,063.4
Total	6835.0	55,959.1
LS Mean Temperature °C		8.2

Maximum Ventilation Rate		
Temperature, °C	Hours with pigs in barn/yr	Temperature × hour
33.6	19.8	665.3
30.8	74.3	2,288.4
28.1	255.4	7,176.7
25.3	424.7	10,744.9
Total	774.2	20,875.3
LS Mean Temperature °C		27.0

Table 7. Hours and least square mean temperature for different cooling scenarios with no pigs in barn

Ventilation Rate Increased to Maintain Room Temperature		
Temperature, °C	Hours with pigs in barn/yr	Temperature × hour
22.5	0.2	4.5
19.7	0.8	15.8
16.9	2.6	43.9
14.2	4.3	61.1
11.4	5.3	60.4
Total	13.2	185.7
LS Mean Temperature °C		14.1

Table 8. Summary of annual non-solar energy use for controlling thermal environment of a 1,200 head grow-finish swine facility in Mason City, Iowa

Process	Duration, hr	Heat, GJ	Electricity, GJ
Heat for pigs	1,063.2	210.8	0
Maintain air quality for pigs	8,672.3	0	31.2
Cooling pigs	7,609.2	0	21.2
Maintain temperature of empty barn	47.8	1.7	0
Maintain air quality when barn empty	87.6	0	0.6
Totals for year		212.5	53.0

APPENDIX 2. CROP PRODUCTION MODEL

Corn grain is the single largest input into modern Iowa pig production. Marketing grain through livestock has been and continues to be the primary destination for Iowa grain crops (ICPB/ICGA, 2009). It is apparent that Iowa pig and crop production are linked. However, crop production is rarely considered within the context of pig feed production. Pig production decisions are often made without full consideration of the potential for crop × pig synergy. The following model was designed to evaluate crop management choices as they pertain to production of pig feed. The crop production model was used to estimate non-solar energy use and 100-yr global warming potential (GWP) of selected crops and cropping sequences. Results from the crop production model are summarized and included for reference purposes. Results from the described model can be linked with other information on feed ingredient processing to generate life cycle assessments of Iowa pork production systems as well as help evaluate crop management decisions within the context of pig feed production.

MODEL DESCRIPTION AND ASSUMPTIONS

Table 1 presents initial conditions of the soil, annual inputs, and expected crop production assumptions for the crop production model. The model assumes that growing conditions for the various crops are ideal except for the absences of abundant nitrogen, phosphorus, and potassium. Initial buffer pH of the soil was set at 6.5 with calcium carbonate as limestone to be applied as needed to support crop production. The soil was assumed to have an initial nitrate-nitrogen concentration (NO^{-}_{3}–N) of 0 ppm with additional synthetic nitrogen applied to fields according to Iowa State University recommendations (ISU, 2003). The crop production model assumed that soil began at the optimal concentration of phosphorus and potassium and that those nutrients are applied at crop removal rates (Sawyer et al., 2002). Anhydrous ammonia (NH_3), diammonium phosphate (DAP), and muriate of potash (MOP) were the primary synthetic source of nitrogen, phosphorus, and potassium considered (Bhat et al., 1994). Diammonium phosphate delivers both phosphorus and nitrogen. Credit was given for any nitrogen applied as DAP and subtracted from the amount to be applied as NH_3.

Chemical herbicide was used to address weeds in corn and soybeans. Annually, two separate applications of herbicide were assumed for both corn and soybeans with application rate and specific active ingredient used for each crop taken directly from USDA reports for the state of Iowa (NASS, 2007). Chemical herbicide use by state is reported by the National Agricultural Statistics Service of USDA (NASS, 2007). The most recent year compiled for corn was 2005, during that year 4 active ingredients—atrazine, acetochlor, s. metolachlor, and glyphosate—accounted for 87% of all herbicide applied to corn in Iowa (NASS, 2007). The model assumes 1 application of a weighted-average mix of atrazine, acetochlor, and s. metolachlor and a second application of glyphosate in corn. Soybean herbicide use in Iowa was most recently compiled for 2006, during that year, glyphosate was applied to 97% of all soybean acres receiving herbicide (NASS, 2007). The model assumes 2 applications of glyphosate in soybeans. It is assumed that both corn and soybeans are glyphosate resistant varieties. Application rates of specific active ingredients for each crop were taken directly from USDA reports for Iowa (NASS, 2007) and scaled to the modeled area.

Average fuel requirements for farming tasks under typical conditions were the basis for estimating diesel fuel use for field operations (Downs and Hansen, 1998; Hanna, 2001). Road transportation of grain, oilseed, alfalfa hay, oat straw, and corn stover were also estimated. It was assumed that a semi-tractor truck with appropriate trailer would be used to haul harvest products an average of 3.2 km with an average fuel efficiency of 3.0 km/L of diesel fuel. The model assumed a grain trailer with a volume of 33.3 m^3 (Edwards and Clarahan, 2008). A flat-bed trailer with usable cargo area of 7.3 × 3.0 × 3.0 m was modeled for transporting large (2.4 × 1.2 × 0.9 m) square bales of hay, straw, and stover. All calculations assume a trailer that is filled to capacity. Given standardized densities of different grain crops (ASABE, 2008) and reported densities of various plant materials (Börjesson, 1996; Peterolia, 2007) the mass of the loaded semi-tractor and trailer were within Iowa legal weight limits (IDOT, 2007).

Transportation energy for all materials was calculated using mass at harvest moisture content. With the exception of corn grain, all material was harvested at storage moisture contents presented in table 1. As modeled, corn grain was harvested at an average moisture content of 19.5% (grain production = 1.18 kg/m^2) and transported to the on-farm grain processing location. Corn grain typically requires additional drying following harvest. A 4% reduction in mass through drying of corn using typical drying technology was included in the model. The drying system is assumed to require 6.5 MJ/kg of mass reduction with 97% of the energy coming from liquefied petroleum gas and the other 3% from electricity (Bern, 1998; Wilcke, 2004).

The quality of stored grain is maintained by timely aeration to control temperature and moisture content of the grain (MWPS, 1987; Wilcke and Morey, 2002). Grain is consumed throughout the year and so less grain will need to be aerated in April compared to December. Annual energy use for maintenance of stored grain quality for a commercial (3,523.9 m^3 or 100,000 bushel) grain storage unit was estimated taking into consideration linearly decreasing grain stocks (MWPS, 1987; Wilcke and Morey, 2002). The model assumes that each kg of grain produced requires 0.45 kJ of electricity to provide adequate aeration for storage throughout the year.

It is well known that rotating crops affects production. Based on reports from Iowa (Al-Kaisi et al., 2006b, a; Mallarino et al., 2006; Al-Kaisi and Licht, 2007b, a; Mallarino and Licht, 2007; Al-Kaisi, 2008b, a) the crop model assumed growing corn in any of the 4 non-continuous corn scenarios will result in an 11% increase in corn production compared to continuous corn. The crop model also assumed growing soybeans in any rotation would result in a 4% increase over growing soybeans continuously. For the rotations where soybeans are grown less than every other year, annual production was assumed to increase by 8% over continuous soybeans (Mallarino and Licht, 2007).

The model assumes that oats will always be under seeded with alfalfa and that oat production will not be affected by any of the examined rotations. The model assumes no harvestable production of alfalfa during the establishment year. Production in the following year is listed in table 1. Nitrogen fixing legumes can influence soil NO^{-}_{3}–N concentrations experienced by following crops. It is assumed that a nitrogen credit of 4.5, 8.4, and11.2 g/m^2 are provided to the subsequent crop of corn by soybeans, alfalfa planted with oats, and established alfalfa. Complex crop rotations may encourage reduction of herbicide by reducing the total area requiring a specific time-sensitive task such as cultivation of corn and soybeans for early season weed control. Based on Leibman et al. (2008) the weed control regime for the C-S-C-O-A rotation will include herbicide application on corn and soybean at 18% of the rate that is used otherwise accompanied by 1 rotary hoeing operation and 2 field crop cultivations.

The energy used to manufacture a product or service can be referred to as the embodied energy of that product of service. Embodied energy values of seed (Börjesson, 1996; Nagy, 1999; Hill et al., 2006), ground limestone (Hammond and Jones, 2008), synthetic fertilizers and herbicides (Bhat et al., 1994) were used to estimate non-solar energy use for crop inputs. These values were combined with fuel use for field operations, transportation, and crop drying to calculate the total non-solar energy use of the different crop sequences. Emission of greenhouse gases are directly linked to energy use but are influenced by the mix of fuel types. Table 2 presents fuel use distribution and 100-year global warming potential for crop production inputs.

Gross energy (GE) of all production represent the energy that could be gained by simply combusting all grain, oilseed, and biomass produced by a given crop sequence. Net energy (NE) represents the portion of GE that a pig actually uses for growth and maintenance from a particular feedstuff (Ewan, 2001; Whittemore, 2006). Net energy most closely represents the true energy value of a feedstuff relative to pig production and is the energy value of most interest to swine nutritionists (Ewan, 2001; Whittemore et al., 2003; Whittemore, 2006). Starch concentration is another important measure of a product's suitability for human food (Quezada-Cavillo et al., 2006) or pig feed (Sauber and Owens, 2001; Whittemore, 2006). Sauvant et al. (2004) presents the GE, NE available to growing pigs, and the starch content of corn, oats, roasted soybeans, alfalfa hay, and wheat straw. Wheat straw was assumed to be equivalent to oat straw in terms of GE for this analysis. Corn stover was assumed to have a GE value of 14.2 MJ/kg at 15% moisture (Pordesimo et al., 2005). It was assumed that oat straw and corn stover were of very limited value as food or feedstuffs and that NE value and starch content was effectively zero. Crop production model results and literature values were used to calculate GE, NE available to growing pigs, and total starch production for each crop production sequence.

RESULTS

Table 3 presents the estimated annual inputs and crop production parameters for individual crops within different crop sequences. Adding soybeans to the crop sequence reduces anhydrous ammonia needs by 15% and increases grain and stover production relative to continuous corn. With increasing crop production, diammonium phosphate and muriate of potash use also increases. More complex crop rotations drastically reduce the amount of anhydrous ammonia needed by corn. Although rotations that include oats and alfalfa also require additional crop inputs, the total inputs per square meter of farmland in the more complex rotations are less than the combinations of corn and soybeans. Production of corn within more complex rotations increases the productivity of corn as compared to monoculture, but productivity per area of total cropland decreases. For example, if 100 m^2 of cropland is available and it is managed as continuous corn, 70.84 kg of starch will be produced. Alternatively if the 100 m^2 of available cropland is managed under the corn-soybean sequence starch production per m^2 of corn planted increases, but total area planted to corn decreases and only 39.49 kg of starch is produced. This illustrates the importance of considering not only individual crops within a rotation, but also the total impact of a specific crop sequence.

Calculated non-solar energy use and 100-year global warming potential for individual crops within different crop sequences is presented as tables 4 and 5. Reducing crop inputs reduces non-solar energy use and production of greenhouse gases. As expected growing corn in more complex rotations reduces non-solar energy use and 100-year global warming potential for corn production as compared to monoculture. Corn is the most energy intensive crop considered. Thus as corn's relative contribution to a sequence decreases, the non-solar energy use for the entire crop sequence also decreases. For example, 100% of cropland in the C-C sequence is devoted to corn production and the non-solar energy use of cropland managed as continuous corn is 2.44 MJ/m^2. Alternatively the C-C-S, C-S, and C-S-C-O-A sequences assume 66, 50, and 40% of the total cropland area being devoted to corn production. Non-solar energy use of managed cropland is 1.94, 1.56, and 1.43 MJ/m^2 for the C-C-S, C-S, and C-S-C-O-A sequences, respectively. One hundred-year global warming potential follows the same trend of decreasing impacts per m^2 of managed cropland for the more complex sequences as compared to corn managed as a monoculture.

Information about individual crops managed within different crop sequences presented in tables 3–5 is summarized in table 6. Table 6 presents production, non-solar energy inputs, and 100-year global warming potential of 5 different crop sequences. Corn delivers large amounts of material that is high in GE, NE, and starch content. Reducing corn's portion of available cropland by adding other crops to the sequence reduces overall production of GE, NE, and starch. Corn is also the most non-solar energy intensive crop examined and reducing the percentage of area devoted to corn production reduces non-solar energy use and 100-year global warming potential of the entire cropping sequence.

Of greatest interest are the output ratios or yield results presented in table 6. Yield is calculated by simply dividing a measure of output by a measure of input. Within industrial agriculture, the concept of crop yield described as bushel/acre is strongly entrenched, but may give a false sense of productivity. Although farmland is a limited resource that must be considered, non-solar energy requirements for crop production may be even more finite.

Similarly, if financial incentives are offered or regulations are imposed to better manage greenhouse gas emissions, a practical calculation of yield should relate production of desirable end-products (NE or starch) per unit of undesirable co-products (greenhouse gas production). Table 6 includes output ratios which relate GE, NE, and starch production to non-solar energy use and 100-year global warming potential.

Gross energy is a measure of potential energy production that may be particularly important for those focused on bio-fuels or production of other renewable energy resources. However the focus of this paper is crop production in the context of producing feedstuffs for pigs. Net energy is the reported measure of productivity that is of greatest interest to swine nutritionists. Although pigs are not thought to have a starch requirement *per se,* starch is often used as a measure of grain quality and suitability for nonruminant animals and is of interest to nutritionists who work with livestock as well as human nutritionists.

Continuous corn produces the least NE per unit of non-solar energy or 100-year global warming potential. The C-S sequence produces the most net energy per unit non-solar energy. Continuous corn produces the most starch/MJ non-solar input and g CO_2 equivalents. Other than starch production, C-C is not as effective as the other sequences considered. The C-S-C-O-A sequence produces the least amount of starch/ MJ non-solar energy and g CO_2 equivalents. Management of alfalfa requires large amounts of energy-intensive field operations and produces very little NE and no starch for pigs. The C-S-C-O sequence captures many of the energetic benefits of the C-S-C-O-A sequence without devoting any space to production of alfalfa. Because alfalfa is considerably less desirable as a feedstuff for pigs compared to the other crops, the rotational benefits of alfalfa do not outweigh its drawbacks in this analysis. Perennial crops such as alfalfa provide valuable services and should be included in generalized crop sequences. However deriving maximal benefit from forage crops requires inclusion of ruminant animals in the equation. Such analysis and discussion is beyond the scope of this paper. It is important to note that the C-S and C-S-C-O-A sequences perform similarly and that both are superior to C-C in terms of producing both NE and GE/ MJ non-solar energy and g CO_2 equivalents.

The C-S sequence produces the most NE/MJ non-solar energy input and g CO_2 equivalents. The C-S-C-O sequence is the best alternative sequence in terms of starch and net energy production per unit of non-solar energy input and g CO_2 equivalents. A C-S-C-O-A sequence may offer several advantages for systems that include ruminants, but in terms of producing pig feed it is not as well suited as the C-S or C-S-C-O sequences.

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Table 1. Initial conditions of the soil, annual inputs, and expected crop production[1,2].

	Corn	Soybean	Oat	Alfalfa
Seed production[3], kg/m^2	1.13	0.33	0.43	0
Seed dry matter at harvest[4], %	80.5	87.0	86.0	Na
Harvestable biomass[3], kg/ m^2	0.94	0	0.21	0.9
Biomass dry matter at harvest, %	85.0	na	92.0	92.0
Soil buffer pH	6.5	6.5	6.5	6.5
$CaCO_3$ application[5], kg/ m^2	0.3	0.3	0.3	0.7
Soil test nitrate, ppm N	0	0	0	0
N application[6], g/ m^2	24.2	0	10.1	0
P_2O_5 application, g/ m^2	7.6	4.8	5.4	5.6
K_2O_5 application, g/ m^2	6.0	9.1	13.4	17.9
Seed[7]	7.9	40.9	5.6	1.8
Herbicide[8,9], g a.i. / m^2	0.25	0.14	0	0

[1] Values represent average production and total inputs for one calendar year of continuous corn, continuous soybeans, oats under seeded with alfalfa and alfalfa following establishment.

[2] Based on Sawyer et al. (2002) unless otherwise stated.

[3] Grain and harvestable biomass (corn stover, oat straw, alfalfa hay) equivalent to 180, 54, 120 bushel/acre and 4.0 ton/acre at 84.5, 87.0, 86.0, and 85.0% dry matter for corn, soybean, oat, and alfalfa respectively.

[4] Corn grain will be dried to 84.5% dry matter for storage, all other crops are harvested at storage moisture content.

[5] Assumes 15.24 cm of soil depth to be neutralized.

[6] Nitrogen from PM 1811 ISU 2003.

[7] Corn and soybeans are given as seed/m^2; oats and alfalfa presented as g seed/m^2.

[8] Based on NASS (2007).

[9] Active ingredient

Table 2. Fuel use distribution assumptions and 100-year global warming potential for crop production inputs.

Input	Electricity, %	Diesel, %	Liquefied Petroleum Gas, %	Total GWP[1], kg CO_2/GJ
Seed	2.5	2.5	95.0	67.79
Limestone	0	100	0	82.73
Anhydrous ammonia[2]	2.6	0	97.4	67.47
Diammonium phosphate[2]	4.5	0.2	95.3	70.67
Muriate of potash[2]	4.3	0	95.7	70.30
Herbicide[2]	3.0	0	97.0	68.14
Field operations	0	100	0	82.73
Transportation	0	100	0	82.73
Drying of corn grain	3.0	0	97.0	75.02
Aeration of stored grain	100	0	0	229.32

[1] 100-year Global warming potential (IPCC, 2006, 2007; EPA, 2008).
[2] Based on Bhat et al. (1994).

Table 3. Estimated annual inputs and crop production parameters for individual crops within different crop sequences[1].

Sequence	C-C	C-S		C-C-S		C-S-C-O			C-S-C-O-A			
Crop	Corn	Corn	Soybean	Corn	Soybean	Corn	Soybean	Oat	Corn	Soybean	Oat	Alfalfa
Limestone, kg/m^2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Anhydrous ammonia, g/m^2	25.8	23.2	0	26.0	0	20.8	0	9.7	14.0	0	9.7	0
Diammonium phosphate, g/m^2	16.8	18.7	11.2	18.7	11.6	18.7	11.6	12.0	18.7	11.6	12.0	12.5
Muriate of potash g/m^2	10.1	11.2	15.7	11.2	16.3	11.2	16.2	22.4	11.2	16.2	22.4	29.9
Herbicide[2], mg a.i./m^2	252.8	252.8	138.1	252.8	138.1	252.8	138.1	0	207.3	113.2	0	0
Seed production[3], kg/m^2	1.13	1.26	0.38	1.26	0.39	1.26	0.39	0.43	1.26	0.39	0.43	0
Stover/straw/hay, kg/m^2	0.94	1.04	0	1.04	0	1.04	0	0.21	1.04	0	0.21	0.90
Gross energy[4], MJ/m^2	31.25	34.73	7.76	34.73	7.97	34.73	7.97	10.79	34.73	7.97	10.79	14.90
Net energy[4], MJ/m^2	12.27	13.68	4.10	13.68	4.21	13.68	4.21	3.57	13.68	4.21	3.57	3.20
Starch[4], g/m^2	708.40	789.90	0	789.90	0	789.90	0	151.96	789.90	0	151.96	0

[1] C-C= continuous corn, C-S = corn-soybean; C-C-S = corn-corn-soybean; C-S-C-O = corn, soybean, corn, oat under seeded with alfalfa; C-S-C-O-A = corn, soybean, corn, oat under seeded with alfalfa, alfalfa hay

[2] Active ingredient

[3] Seed production reported at storage moisture content of 15.5, 13.0, and 14.0% for corn, soybeans, and oats respectively

[4] Corn at 84.5% dm = 15.84 MJ/kg GE, 10.85 MJ/kg NE, 62.69% starch
Corn stalks 14.2 MJ/kg as harvested
Full-fat soybeans at 87% dm = 20.42 MJ/kg GE, 10.80 MJ/kg NE, 0% starch
Oats at 86% dm = 16.79 MJ/kg GE, 7.81 MJ/kg NE, 35.34% starch
Oat straw 16.9 MJ/kg as harvested
Alfalfa 17-18% protein as dry matter; 90.6% dm = 16.3 MJ/kg GE; 3.5 MJ/kg NE

Table 4. Calculated non-solar energy use (kJ/m^2) for individual crops within different crop sequences[1].

Sequence	C-C	C-S		C-C-S		C-S-C-O			C-S-C-O-A			
Crop	Corn	Corn	Soybean	Corn	Soybean	Corn	Soybean	Oat	Corn	Soybean	Oat	Alfalfa
Seed	21.5	21.5	42.0	21.5	42.0	21.5	42.0	40.3	21.5	42.0	40.3	63.0
Limestone	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	360.0
Anhydrous ammonia	1,235.8	1,126.7	0	1,259.9	0	1,011.3	0	469.7	679.8	0	469.7	0
Diammonium phosphate	332.2	360.1	220.5	360.1	228.3	369.1	228.3	236.2	369.1	228.3	236.2	246.1
Muriate of potash	93.1	103.4	144.8	103.4	150.0	103.4	150.0	206.9	103.4	150.0	206.9	275.8
Herbicide	81.9	81.9	62.7	81.9	62.7	81.9	62.7	0	67.1	51.4	0	0
Field operations	161.8	161.8	92.8	161.8	92.8	161.8	92.8	124.9	161.8	92.8	124.9	266.5
Transport of grain	21.5	23.9	6.5	23.9	6.7	23.9	6.7	13.8	23.9	6.7	13.8	0
Drying of grain	293.7	326.3	0	326.3	0	326.3	0	0	326.3	0	0	0
Aeration of stored grain	0.5	0.6	0.2	0.6	0.2	0.6	0.2	0.2	0.6	0.2	0.2	0
Bale oat straw	0	0	0	0	0	0	0	42.3	0	0	42.3	0
Transport of straw/hay	0	0	0	0	0	0	0	7.8	0	0	7.8	8.1
Bale cornstalks	22.3	22.3	0	22.3	0	22.3	0	0	22.3	0	0	0
Transport cornstalks	30.0	33.2	0	33.2	0	33.2	0	0	33.2	0	0	0
Total, kJ/m^2	2,444.3	2,411.7	719.5	2,544.9	732.7	2,305.3	732.7	1,292.1	1,959.0	721.4	1,292.1	1,219.5
Average, kJ/m^2	2,444.3	1,565.6		1940.8		1,658.8			1,430.2			

[1] C-C= continuous corn, C-S = corn-soybean; C-C-S = corn-corn-soybean; C-S-C-O = corn, soybean, corn, oat under seeded with alfalfa; C-S-C-O-A = corn, soybean, corn, oat under seeded with alfalfa, alfalfa hay

Table 5. Calculated 100-year global warming potential (g CO_2 equivalents/m^2) for individual crops within different crop sequences[1].

Sequence	C-C	C-S		C-C-S		C-S-C-O			C-S-C-O-A			
Crop	Corn	Corn	Soybean	Corn	Soybean	Corn	Soybean	Oat	Corn	Soybean	Oat	Alfalfa
Seed	1.5	1.5	2.8	1.5	2.8	1.5	2.8	2.7	1.5	2.8	2.7	4.3
Limestone	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	29.8
Anhydrous ammonia	84.6	76.0	0	85.0	0	68.2	0	31.7	45.9	0	31.7	0
Diammonium phosphate	23.5	25.4	15.6	25.4	16.1	26.1	16.1	16.7	26.1	16.1	16.7	17.4
Muriate of potash	6.5	7.3	10.2	7.3	10.5	7.3	10.5	14.5	7.3	10.5	14.5	19.4
Herbicide	5.6	5.6	4.3	5.6	4.3	5.6	4.3	0	4.6	3.5	0	0
Field operations	13.4	13.4	7.7	13.4	7.7	13.4	7.7	10.3	13.4	7.7	10.3	22.0
Transport of grain	1.8	2.0	0.5	2.0	0.6	2.0	0.6	1.1	2.0	0.6	1.1	0
Drying of grain	22.0	24.5	0	24.5	0	24.5	0	0	24.5	0	0	0
Aeration of stored grain	0.1	0.1	0	0.1	0	0.1	0	0	0.1	0	0	0
Bale oat straw	0	0	0	0	0	0	0	3.5	0	0	3.5	0
Transport of straw/hay	0	0	0	0	0	0	0	0.6	0	0	0.6	0.7
Bale cornstalks	1.8	1.8	0	1.8	0	1.8	0	0	1.8	0	0	0
Transport cornstalks	2.5	2.7	0	2.7	0	2.7	0	0	2.7	0	0	0
Total, g/m^2	175.7	172.7	53.5	181.7	54.4	165.6	54.4	93.5	142.3	53.6	93.5	93.6
Average, g/m^2	175.7	113.1		139.3		119.8			105.1			

[1] C-C= continuous corn, C-S = corn-soybean; C-C-S = corn-corn-soybean; C-S-C-O = corn, soybean, corn, oat under seeded with alfalfa; C-S-C-O-A = corn, soybean, corn, oat under seeded with alfalfa, alfalfa hay

Table 6. Summary of production, non-solar energy inputs, and 100-year global warming potential for 5 crop sequences[1].

Sequence	C-C	C-S	C-C-S	C-S-C-O	C-S-C-O-A
Gross energy, MJ/m^2	31.25	21.25	25.81	22.06	20.62
Net energy, MJ/m^2	12.27	8.89	10.52	8.79	7.76
Starch, g/m^2	708.40	394.95	526.60	432.94	346.35
Non-solar energy, MJ/m^2	2.44	1.57	1.94	1.66	1.43
100-yr GWP[2], g CO_2 equivalents/m^2	175.70	113.10	139.3	119.8	105.1
Output Ratios					
Gross energy : non-solar energy	12.81	13.54	10.95	13.29	14.42
Net energy : non-solar energy	5.03	5.66	5.42	5.29	5.43
Starch : non-solar energy	290.33	251.56	271.44	260.81	242.20
Gross energy : 100-yr GWP	0.18	0.19	0.19	0.18	0.20
Net energy : 100-yr GWP	0.07	0.08	0.07	0.07	0.07
Starch : 100-yr GWP	4.03	3.49	3.78	3.61	3.30

[1] CC= continuous corn, C-S = corn-soybean; C-C-S = corn-corn-soybean; C-S-C-O = corn, soybean, corn, oat under seeded with alfalfa; C-S-C-O-A = corn, soybean, corn, oat under seeded with alfalfa, alfalfa hay

[2] 100-yr GWP = 100-year global warming potential

APPENDIX 3: PIG FEED INGREDIENT MANUFACTURING AND DELIVERY: PROCESS INVENTORY AND ASSUMPTIONS

This section examines the energy required to prepare a complete and balanced pig diet at a commercial feed mill typical of Iowa including transportation distance and fuel efficiency assumptions. The energy required to process corn, oats, and soybeans into primary feed ingredients—ground corn, ground oats, roasted soybeans, soy oil, and soybean meal is reported. The energetics of corn-grain ethanol and soy oil-based biodiesel in the context of pig feedstuff creation is also reviewed. The energy and subsequent emissions of greenhouse gases required to process, manufacture, or synthesize ground limestone, moncalcium phosphate, phytase, L-lysine, and DL-Methionine are estimated based on reviewed literature. Non-solar energy use and 100-yr global warming potential (GWP) are reported per kg of feed ingredient or complete and balanced diet.

TRANSPORTATION AND DIET MIXING

Many pig diet ingredients are produced near the site of diet formulation and pig production, some are not. The model assumes that transportation of distances ≥ 200 km occurs via freight train. The energy intensity of moving freight via U.S. railroads is reported as 0.2 kJ × kg•km^{-1} (Davis et al., 2008). For transportation of distances < 200 km a semi-tractor truck with fuel efficiency of 2.2 km/L is assumed (Davis et al., 2008). A reported 33.3 m^3 trailer volume (Edwards and Clarahan, 2008) and 24,000 kg towing capacity are also assumed. It is estimated that the energy intensity of moving freight via the described semi-tractor and trailer is 0.7 kJ × kg•km^{-1}. Assumed transportation distances for each feed ingredient are detailed in table 1. It is assumed that 100% of transportation fuel is diesel fuel.

Energy associated with weighing ingredients, moving ingredients and mixed diets inside of the feed mill, and mixing of the final diet is assumed to originate as electricity. Based on discussions with commercial feed mill operators and equipment manufacturers it is estimated that all activities associated with mixing and moving material inside the feed mill requires 2.1 kJ/kg.

PRIMARY FEED INGREDIENTS

Cereal grains such as corn and oats are almost always ground and mixed with other ingredients before being fed to pigs. Reducing particle size of cereal grains to ≤ 600 μm results in improvements in nutrient digestion, absorption, and metabolism in pigs (Hancock and Behnke, 2001). Reducing feed particle size to ≤ 400 μm improves some measures of productivity in growing pigs (Healy et al., 1994; Wondra et al., 1995a) and energy utilization in lactating sows (Wondra et al., 1995c). However diets with particle size ≤ 400 μm have also been shown to increase the severity of stomach ulceration in finishing pigs (Wondra et al., 1995a) and lactating sows (Wondra et al., 1995c). Flowability of finely ground diets can be problematic, requiring more attention to adjustment of feeders. For this analysis it is assumed that the target feed particle size is 600 μm.

Although both hammermills and roller mills are common in the US feed industry, roller mills offer several advantages in pig diet manufacture. Greater apparent nutrient digestibility has been reported in finishing pigs fed corn ground using a roller mill compared to hammermilled corn (Wondra et al., 1995b). It is also generally accepted that operation of roller mills requires less energy/kg of feed processed compared to hammermills (Hancock and Behnke, 2001). Wondra et al. (1995b) report energy use of 38.9 kJ/kg for a roller mill compared to 51.2 kJ/kg for a hammermill when milling corn to a mean particle size of 400 μm. Energy consumption by a commercial feed mill is expected to be considerably less per kg of material ground. Based on discussions with commercial feed mill operators and equipment manufacturers it is estimated that processing 1,000 kg of material to 600 μm in a commercial roller mill typical of what is used in Iowa for processing pig feed will require 15.6 MJ and 104 seconds.

Raw soybeans have been effectively fed to gestating sows (Crenshaw and Danielson, 1985). Other researchers have reported that finishing pigs fed diets containing amino acid-supplemented raw soybeans perform similarly to pigs fed corn-soybean meal control diets (Southern et al., 1990). Raw soybeans contain several anti-nutritional factors, particularly trypsin inhibitors which disrupt protease activity and reduce protein digestion and utilization (De Schutter and Morris, 1990; van Heugten, 2001). Simple heat treatment or roasting of raw soybeans destroys the trypsin inhibitors and other anti-nutritional factors in soybeans (De Schutter and Morris, 1990). Roasted, full-fat soybeans contain all the soy oil and amino acids present in raw soybeans without the anti-nutritional factors. Feeding roasted, full-fat soybeans—a high energy, amino acid rich feedstuff—to pigs results in equal or superior performance to pigs fed soybean meal as a protein supplement (De Schutter and Morris, 1990). Based on conversations with commercial grain roasters it is estimated that processing 1,000 kg raw soybeans into roasted, full-fat soybeans requires 536.9 MJ energy from liquefied petroleum gas (LP gas) and 37.0 MJ energy from electricity. Following roasting, full-fat soybeans are ground before being mixed with other diet ingredients. As with corn and oats, our model assumes that processing roasted, full-fat soybeans to 600 μm in a commercial roller mill requires 15.6 kJ/kg of material.

Roasted, full-fat soybeans are not a common feedstuff for pigs in Iowa because of the historic profit potential in separating soybean oil and meal. Soybean meal is often directed to animal feed, but most soybean oil is marketed to higher value end-users. Processing soybeans into soybean meal and soy oil is a multi-step process that requires significant amounts of energy input (Erickson, 1995; Li et al., 2006; Dalgaard et al., 2008; Huo et al., 2008). Efficiency of soybean processing plants is not 100% with literature values ranging from 78.6–82.0% for the conversion of soybeans into soybean meal (Woerfel, 1995; Li et al., 2006; Dalgaard et al., 2008). Similarly 15.8–17.8% of a given mass of soybeans will be manufactured into soy oil (Woerfel, 1995; Li et al., 2006; Dalgaard et al., 2008). For our analysis we assume that 100 kg of soybeans will be processed into 80 kg soybean meal and 17 kg soy oil, with the remaining 3 kg being lost.

When a process has two or more usable products, the energy required for processing is allocated between the products. Because this analysis is focused on pig feed production, we will allocate processing energy based on net energy (NE) and mass of feedstuffs produced. For example, processing 100 kg of soybeans results in 80 kg soybean meal with a NE for growing pigs of 8.4 MJ/kg (Sauvant et al., 2004). In addition to soybean meal, 17 kg soybean oil with a NE for growing pigs of 29.8 MJ/kg (Sauvant et al., 2004) is also generated. Processing of 100 kg of soybeans into soybean meal and soy oil thus results in the production of 1,178.6 MJ NE for growing pig. We attribute 57% of soybean production and processing energy to soybean meal and 43% to soy oil based on the NE of the final product mass. Literature values of energy use for processing of soybeans into soybean meal and soybean oil range between 0.47 MJ/kg (Dalgaard et al., 2008) and 2.66 MJ/kg (Huo et al., 2008). For this analysis we assume soybean processing requires 0.60 MJ/kg. This equates to

0.34 MJ/kg of soybean meal and 0.26 MJ/kg of soy oil. Following previous reviews (Li et al., 2006; Dalgaard et al., 2008; Huo et al., 2008), we estimate that 91% of the energy associated with soybean processing is LP gas and 9% is electricity.

BIOFUEL CO-PRODUCTS

The energy balance of biofuels is affected by the inputs required to produce raw materials and how those raw materials are refined into biofuels. Clearly defining system boundaries is essential for a meaningful discussion of biofuels. Our analysis of biofuel production is focused on implications for pig diets. We assume that the raw materials used for biofuel production are corn grain and soy oil for ethanol and biodiesel production respectively. The co-product of ethanol fermentation is dried distiller's grains with solubles (DDGS). The co-product of biodiesel refining is crude glycerol. We assume that the corn and soybeans are grown in a corn-soybean sequence. The cultivation and processing energy of soybeans is divided between soy oil and soybean meal based on NE of the total mass of products. Only the energy attributed to soy oil is included in the biofuel analysis. The distribution of energy and 100-yr global warming potential for the production of biofuels and their co-products is presented in tables 2 and 3.

Generating ethanol from corn grain and biodiesel from soy oil necessarily forgoes the opportunity of feeding those feedstuffs to pigs. Thus when examining biofuels in the context of pig feed production the cultivation energy of the feedstock, the processing energy of converting the feedstock into biofuel and co-product, the energetic value of the biofuel and co-product, and the NE of the feedstock not fed to pigs are considered. The NE of corn grain and soy oil are 11.1 MJ/kg and 29.8 MJ/kg respectively (Sauvant et al., 2004) and our analysis incorporates the NE opportunity cost of converting these materials into biofuels and co-products as opposed to directly feeding corn or soy oil to pigs. We attribute 100% of the NE of the feedstock not fed to pigs to ethanol and biodiesel. Dried distillers grains with solubles and crude glycerol are co-product feedstuffs that would never be created except for the production of ethanol and biodiesel. All other energy inputs are divided between the biofuel and co-product based on proportion of useful energy in the final products.

The allocation of processing energy between biofuel and co-products influences the energy balance of biofuel production (Shapouri et al., 2002; Hill et al., 2006; Huo et al., 2008). For every 1,000 kg of corn entering ethanol processing facilities, 417.3 L ethanol is generated and 303.6 kg DDGS is co-produced (ISU, 2008). The gross energy (GE) of corn-grain ethanol is assumed to be 21.3 MJ/L (Hill et al., 2006) while the density is 0.80 kg/L (Blei and Odian, 2000). The NE of DDGS when fed to pigs is 7.0 MJ/kg (Sauvant et al., 2004). Thus processing 1,000 kg corn grain into ethanol and DDGS results in 11.0 GJ useful energy (biofuel + coproduct). Of the total useful energy, 81% is attributed to ethanol with the remaining 19% attributed to DDGS. Therefore 81% of the energy used during the production process is allocated to ethanol and the remaining 19% is allocated to DDGS in our analysis.

Another important co-product of ethanol production is CO_2 released during fermentation. It has been reported that 23% of the total CO_2 emissions from production of ethanol is from the actual fermentation of feedstock and that 100% of emissions from fermentation processes are captured (Möllersten et al., 2003). It has also been reported that 54% of the total CO_2 emissions released during consumption of processing energy related to corn grain ethanol production and fermentation of corn is captured (Möllersten et al., 2003). Some biorefineries capture and sell CO_2 from ethanol plants to the beverage industry or manufacturers of dry ice (ISU, 2008; Vogel, 2008). This CO_2 eventually makes its way to the atmosphere and so is not sequestered, but rather delayed. Sequestration of CO_2 by biofuel producers is a prospect (Möllersten et al., 2003; Lindfeldt and Westermark, 2008) but no dry-mill ethanol plant in Iowa reports capturing CO_2 for long-term sequestration (IADNR, 2008). Our analysis assumes zero net emissions of CO_2 and other greenhouse gases from the actual fermentation of corn grain. Our analysis does include emissions of greenhouse gases associated with non-solar energy use in the processing of grain into ethanol and DDGS.

Estimated energy use for conversion of corn into ethanol and DDGS through the dry-milling process range from 12.7–13.6 MJ/L ethanol (Shapouri et al., 2002; Hill et al., 2006). Our analysis assumes 13.2 MJ/L of ethanol production. Energy used for production of ethanol and its co-product is divided between thermal energy and electricity (Shapouri et al., 2002). It is estimated 74% of the energy used for processing corn into ethanol and DDGS is from LP gas and 26% is from electricity (Shapouri et al., 2002).

Processing soybean oil into biodiesel requires energy, reagents, and solvents and results in co-production of crude glycerol (Hill et al., 2006; Huo et al., 2008). For every 1.0 kg of soybean oil processed, 1.0 kg of biodiesel and 0.1 kg co-products (glycerol, salts, and other impurities) are generated (Huo et al., 2008). The mass of end-products is greater than the mass of soybean oil entering the refinement process because of the addition of solvents and reagents. Hill et al. (2006) included the production energy of solvents and reagents used in biodiesel production and estimated that every 1.0 kg of soybean oil processed requires 1.0 MJ of steam energy and 0.1 MJ of electricity. This compares with the estimated 1.0 MJ of natural gas and 0.05 MJ of electricity presented by Huo et al. (2008). For this analysis we assume that each kg of soybean oil processed requires 1.0 MJ of natural gas and 0.1 MJ of electricity. For every 1.0 L of biodiesel produced, it is estimated that 79 g of crude glycerol is generated (Thompson and He, 2006). The GE of biodiesel used in previous analyses range from 32.9 to 36.1 MJ/L (Hill et al., 2006; Huo et al., 2008). Our analysis assumes the GE of biodiesel is 34.5 MJ/L. A reported density of 0.89 kg/Lwas also assumed for biodiesel (Huo et al., 2008).

Crude glycerol is a substance that until recently received little attention as a feedstuff for pigs in the United States. Lammers et al. (2008) reported a digestible energy (DE) value of 14.0 MJ/kg. Net energy of crude glycerol fed to pigs has not been determined. The ratio of NE to DE is variable for feedstuffs with a typical range of 0.68–0.72 (Whittemore et al., 2003). A ratio of NE to DE of 0.71 is commonly used for conversion of DE to NE (Whittemore et al., 2003). Multiplying the reported DE of crude glycerol (Lammers et al., 2008) by 0.71 results in a predicted NE value that is similar to the theoretical NE value calculated using prediction equations for swine feedstuffs (Sauvant et al., 2004). The NE of crude glycerol fed to growing pigs is estimated as 9.9 MJ/kg in this analysis.

For every 1,000 kg of soybean oil entering biodiesel processing facilities, 890 L of biodiesel and 70.3 kg of crude glycerol are produced. This results in the generation of 31.4 GJ useful energy (biofuel + co-product). Producing this useful energy requires 1.0 GJ of LP gas and 0.1 GJ electricity. Based on useful energy generated, 98% of processing energy is allocated to the biodiesel with 2% allocated to crude glycerol.

MICRO-INGRDIENTS

The mirco-ingredients—minerals, vitamins, sythetic amino acids, and enzymes—typical account for 5% of the total mass of pig diets fed. Our analysis focuses on salt, ground limestone, and monocalcium phosphate because those 3 ingredients account for most of the mass among the micro-ingredients. The enzyme phytase and synthetic amino acids L-Lysine and DL-Methionine are also included because they have an impact on nitrogen and phosphorus utilization and cycling within pig production systems that is disproportionate to their relative mass.

Ground limestone is added to pig diets as a source of Ca. The energy to produce 1.0 kg of ground limestone is reported as 2.5 MJ with 97% of the energy coming as LP gas and the remaining 3% as electricity (LaHore and Croke, 1978). It is calculated that production of ground limestone results in emission of 173.4 g CO_2 equivalents (IPCC, 2006; EPA, 2008). Salt is added to pig diets as a source of Na and as a stimulant of feed intake. The energy to produce 1.0 kg of salt is reported as 1.6 MJ with 65% of the energy coming as electricity and the remaining as LP gas (LaHore and Croke, 1978). Producing 1.0 kg of salt is calculated to result in emission of 279.8 g CO_2 equivalents (IPCC, 2006; EPA, 2008). The processing energy values reported by LaHore and Croke (1978) are for feed production in Australia and are more than 30 years old. It is assumed that techniques and efficiencies for limestone and salt production in Australia are similar to Iowa. It is reasonable that incremental improvements in processing efficiency have occurred over time. Because limestone and salt require relatively little processing energy and comprise $\leq$ 5% of the diet, the error introduced by using processing energy values from 1978 is assumed to be negligible.

Monocalcium phosphate, $Ca(H_2PO_4)_2$, is a highly available inorganic source of phosphorus (P) that is commonly used in pig diets. Environmental impact potential associated with production of monocalcium phosphate (MCP) has been reported (Nielsen and Wenzel, 2006). It is estimated that producing 1.0 kg of MCP requires 13.8 MJ of energy and results in emission of 1,103.4 g of CO_2 equivalents (Nielsen and Wenzel, 2006).

Plants incorporate P into their structures that are generally inaccessible to the digestive tract of pigs. Feeding pigs the enzyme phytase enables utilization of plant source P. This in turn allows reduction of inorganic P sources required to meet the needs of pigs and reduces the excretion of P to the environment (Crenshaw, 2001; Wathes and Whittemore, 2006; Whittemore, 2006). Environmental impacts associated with production of a commercial form of phytase—Ronozyme® P5000 CT—through fungal fermentation has been examined (Nielsen et al., 2006; Nielsen and Wenzel, 2006). Impact values presented by Nielsen and Wenzel (2006) take into consideration benefits derived from reduced use of MCP. Use of the cradle-to-gate values presented by Nielsen et al. (2006) is more appropriate for our analysis because it enables balanced comparison of more specific dietary formulation strategies. Our analysis assumes that production of 1.0 kg phytase requires 40 MJ and results in emission of 2,000 g CO_2 equivalents (Nielsen et al., 2006).

Synthetic amino acids enable more precise matching of diet formulation with the nutritional requirements of the pig. This in turn optimizes amino acid utilization and minimizes excretion of nitrogen (N) by the pig. Lysine and methionine are generally the first and second limiting amino acids in pig diets. This is because of the relatively low amounts of these amino acids found in typical feed ingredients relative to the pig's needs.

Commercial synthesis of L-lysine through bacterial fermentation is well established with an estimated 800,000 metric tons produced annually (Anastassiadis, 2007). The process of bacterial fermentation is widely understood and discussed (Hilliger et al., 1984; Gerhartz et al., 1985; Anastassiadis, 2007). However information necessary to determine the energy use and 100-yr global warming potential associated with L-lysine synthesis is generally regarded as proprietary information. Thus a simplified model of L-lysine synthesis is presented and used to estimate energy use and 100-yr global warming potential of this feed ingredient.

Synthesis of L-lysine occurs through aerobic biosynthesis by selected strains of bacteria (Gerhartz et al., 1985; Anastassiadis, 2007). There are four basic components of bioreactors used for biosynthesis of L-lysine—a carbon rich substrate, a source of nitrogen, selected strains of bacteria, and aeration (Hilliger et al., 1984; Anastassiadis, 2007). Molasses and ethanol are the most common substrates for bacterial fermentation of L-lysine although other carbon sources can be used (Hilliger et al., 1984). Our simplified model assumes that ethanol (C_2H_6O) is the primary source of carbon and that anhydrous ammonia (NH_3) is the source of nitrogen (Anastassiadis, 2007). Identifying a specific microorganism for use in this simplified model is not necessary, rather the authors assume a strain capable of yielding 45 g L-lysine for every 100 g of ethanol is used. This yield falls within the range of reported productivity for developed strains of microorganisms (Anastassiadis, 2007). Microbial synthesis of L-lysine is an aerobic process (Hilliger et al., 1984; Anastassiadis, 2007). A model for predicting energy use for aeration in L-lysine fermentation has been proposed by Hilliger et al. (1984). If a 25 m^3 commercial fermentation vat is used, the power input necessary for maintaining aerobic conditions is estimated as 129.6 MJ/hr (Hilliger et al., 1984). Continuous flow of the fermentation process has several advantages under commercial production conditions (Anastassiadis, 2007) and our model assumes a continuous flow process. Microbial fermentation is a biological process and thus necessarily requires time. Based on literature reports it is assumed that 48 hours pass between the time a particular molecule of ethanol enters the fermenter and its carbon atoms exit as L-lysine or co-products of fermentation (Hilliger et al., 1984; Gerhartz et al., 1985; Anastassiadis, 2007).

Post-fermentation drying of the L-lysine fermentation broth is necessary to produce the solid feed additive most commonly used in pig diets (Anastassiadis, 2007). Removal of water is estimated to require 6.5 MJ/kg of water with 97% of the energy consumed as LP gas and the remaining 3% as electricity (Bern, 1998; Wilcke, 2004). The 100-yr GWP of drying activity is calculated as 0.44 kg CO_2 equivalents per kg of water removed (IPCC, 2006; EPA, 2008). The simplified model of L-lysine synthesis through bacterial fermentation is presented as equation 1.

Equation 1: Simplified model of L – lysine synthesis through bacterial fermentation

$$2{,}222\ g\ C_2H_6O + 232\ g\ NH_3 \xrightarrow{0.63\ MJ\ aeration} 1{,}000\ g\ Lysine + 6.5\ g\ H_2O$$

$$1{,}000\ g\ Lysine + 6.5\ g\ H_2O \xrightarrow{0.04\ MJ\ drying} 1{,}000\ g\ Lysine$$

The fermentation broth is generally maintained at a temperature of 31–33°C during the entire process (Anastassiadis, 2007). This likely requires the input of some energy as heat. It is also expected that energy from steam generated during the drying process is recycled through the production cycle. Our simplified model assumes no inputs of energy for heating fermentation broth and no recovery of steam generated energy. We estimate that production of 1.0 kg of L-lysine requires 2,222 g (2.8 L) ethanol, 232 g anhydrous ammonia, 0.64 J of processing energy. The energy and 100-yr global warming potential associated with production of anhydrous ammonia and ethanol were also included in the analysis. Production of 2.8 L of ethanol from corn grain produced in a corn-soybean crop sequence was estimated using previously described crop and biofuel production models. It is estimated that cultivating and processing adequate amounts of corn to produce 2.8 L ethanol requires 40.20 MJ and results in emissions of 736.8 g CO_2 equivalents. This estimate does not include the portion of cultivation and processing energy that is allocated to the ethanol co-product, DDGS or the NE of 6.6 kg corn not fed to pigs if processed into 2.8 L ethanol. Producing 232 g anhydrous ammonia is calculated to require 11.3 MJ (Bhat et al., 1994) and result in emission of 762.4 g CO_2 equivalents (Bhat et al., 1994; IPCC, 2006; EPA, 2008).

DL-methionine production through fermentation is possible, however no commercial process utilizing fermentation has been developed due to problems associated with isolation of appropriate strains of microbes (Gomes and Kumar, 2005; Kumar and Gomes, 2005). A chemical process for production of DL-methionine has been recognized for more than 60 years (Goldsmith and Tishler, 1946) and is the exclusive method for production of DL-methionine on a commercial scale (Binder, 2003). The chemical synthesis of 1.0 kg DL-methionine is reported to require 88.0 MJ of energy, the vast majority being delivered as petrochemical raw materials (Binder, 2003). Based on the assumption that 100% of the petrochemical is delivered as LP gas, it is calculated that each 1.0 kg of DL-methionine results in emmisison of 5,557.2 g CO2 equivalents (IPCC, 2006).

RESULTS

Table 4 presents energy use and resulting 100-yr global warming potential associated with preparation and delivery of feed ingredients. Very little processing is required to prepare corn and oats for inclusion in pig diets. Also because feed mills are typically located near the site of grain and pig production, transportation energy for these feedstuffs is less than other feed ingredients. The energy required to produce 1.0 kg of monocalcium phosphate, phytase, L-Lysine, and DL-Methionine are several orders of magnitude larger than energy required to produce primary feed ingredients like corn and soybean meal. Very small quantities of these feed ingredients are used in typical pig diets and their inclusion usually results in nutrient cycling impacts that exceed their relative contribution to the mass of the mixed diet.

CONCLUSIONS

The current inventory of manufacturing and processing energy of pig feed ingredients is an initial step in improved analysis of the implications of pig diet choice in Iowa. This inventory is by no means complete, but it can be linked with the previously described crop production model (Lammers, 2009) to estimate the non-solar energy and 100-yr GWP associated with pig feed production in Iowa. Refinement of this inventory and inclusion of additional feed ingredients is desirable and should continue.

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Table 1. Estimated travel distance[1] and mode of transportation for pig feed ingredients and finished diet in Iowa.

	Mode of Transportation		
Activity	Semi-tractor, Km	Railroad, km	Energy, kJ/kg
Grain delivery to feed mill	12	0	8.4
Roasted soybean delivery to feed mill	12	0	8.4
Soybean delivery to soybean processor	130	0	91.0
Soybean meal delivery to feed mill	100	0	70.0
Soy oil delivery to feed mill	100	0	70.0
Soybean oil delivery to biodiesel bio-refinery	0	0	0
Crude glycerol delivery to feed mill	100	0	70.0
Grain delivery to ethanol bio-refinery	48	0	33.6
DDGS delivery to feed mill	36	0	25.2
Ethanol delivery to amino acid processor	0	500	100.0
Synthetic amino acid delivery to feed mill	48	500	133.6
Ground limestone delivery to feed mill	75	0	52.5
Salt delivery to feed mill	75	0	52.5
Monocalcium phosphate delivery to feed mill	48	600	153.6
Phytase delivery to feed mill	48	700	173.6
Delivery of mixed diet to pig production site	12	0	8.4

[1] Values are for round trip distance.

Table 2. Inventory of non-solar energy and 100-yr global warming potential associated with ethanol fermentation and dried distiller's grains co-generation.

	Entire Process	Ethanol	DDGS
Corn input, kg/kg DDGS	3.3		
Biofuel output, L		1.4	
Co-product output, kg			1.0
Useful energy output, MJ	36.8	29.8	7.0
Allocation of impacts, %		81	19
NE of corn not fed[1], MJ	36.6	36.6	0
Production and delivery of corn[2], MJ	6.3	5.1	1.2
Fermentation and drying[3], MJ	18.5	15.0	3.5
Total non-solar energy input energy, MJ	61.4	56.7	4.7
Emissions from cultivation[2], g CO_2 equivalents	440.6	356.9	83.7
Emissions from delivery[3], g CO_2 equivalents	14.2	11.5	2.7
Total emissions, g CO_2 equivalents	454.8	368.4	86.4

[1] Attributed entirely to ethanol because DDGS is a co-product feed that would not be produced except for production of ethanol.

[2] Non-solar energy and associated emissions used to grow, harvest, store, transport, and grind 3.3 kg corn planted in Corn-Soybean sequence with no harvesting of corn stalks.

[3] Non-solar energy and associated emissions used to process 3.3 kg of ground corn into 1.0 kg DDGS and 1.4 L fuel ethanol.

Table 3. Inventory of non-solar energy and 100-yr global warming potential associated with biodiesel refining and crude glycerol co-generation.

	Entire Process	Ethanol	DDGS
Soybean oil kg/kg crude glycerol	14.2		
Biofuel output, L		12.7	
Co-product output, kg			1.0
Useful energy output, MJ	448.1	438.2	9.9
Allocation of impacts, %		98	2
NE of soy oil not fed[1], MJ	426.2	426.2	0
Production and delivery of soy oil[2], MJ	96.2	94.3	1.9
Refining[3], MJ	15.6	15.3	0.3
Total non-solar energy input energy, MJ	538.0	535.8	2.2
Emissions from cultivation[2], g CO_2 equivalents	7,186.0	7,042.3	143.7
Emissions from delivery[3], g CO_2 equivalents	1,228.5	1,203.9	24.6
Total emissions, g CO_2 equivalents	8,414.5	8,246.2	168.3

[1] Attributed entirely to biodiesel because crude glycerol is a co-product feed that would not be produced except for production of biodiesel.

[2] 57% of non-solar energy and associated emissions used to grow, harvest, store, transport, and process 83.6 kg soybeans planted in Corn-Soybean sequence into 14.2 kg soy oil and 66.9 kg soybean meal. Reported value excludes non-solar energy and associated emissions allotted to soybean mean (43% of total).

[3] Non-solar energy and associated emissions used to process 14.2 kg of soy oil into 1.0 kg crude glycerol and 1.4 L biodiesel.

Table 4. Energy use and resulting 100-yr global warming potential associated with producing and delivering swine feed ingredients to feed mill and mixing formulated swine diets in Iowa.

Ingredient	Production Energy[1] kJ/kg	100-yr GWP[1] g CO_2 equivalents/kg
Ground corn	24.0	4.3
Ground oats	24.0	4.3
Full-fat roasted soybeans	597.9	46.7
Soybean meal	501.0	39.9
Soy oil	421.0	33.6
DDGS[2]	4,700.0	86.4
Crude glycerol[3]	2,200.0	168.3
Ground limestone[4]	2,545.0	173.4
Salt[4]	1,635.0	279.8
Monocalcium phosphate[5]	13,800.0	1,104.4
Phytase[6]	40,000.0	2,000.0
L-Lysine	52,170.0	1,642.2
DL-Methionine[7]	88,000.0	5,557.2
Mixing and delivery of diet	10.5	1.2

[1] Does not include energy use or 100-yr global warming potential (GWP) associated with cultivation and storage of grains and oilseeds.

[2] Values include energy and 100-yr GWP required to produce 3.3 kg corn grain in C-S sequence. Values exclude NE of 3.3 kg corn grain not fed to pigs, the gross energy of 1.4 L ethanol that is co-produced, and the potential displacement of other transportation fuels by ethanol. Values assume 0% capture of CO_2 produced by fermentation.

[3] Values include energy and 100-yr GWP required to production 14.2 kg soy oil from C-S sequence. Values exclude NE of 14.2 kg soy oil not fed to pigs, the gross energy of 12.7 L of biodiesel that is co-produced, and the potential displacement of other transportation fuels by biodiesel.

[4] (LaHore and Croke, 1978).

[5] (Nielsen and Wenzel, 2006).

[6] (Nielsen et al., 2006).

[7] (Binder, 2003).

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