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Life cycle assessment of high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States

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ABSTRACT

We used ISO-compliant life cycle assessment to evaluate the comparative environmental performance of high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States. Specifically, we evaluated the contributions of feed production, in-barn energy use, manure management, and piglet production to farm-gate life cycle energy use, ecological footprint, and greenhouse gas (GHG) and eutrophying emissions per animal produced and per live-weight kg. We found that commodity systems generally outperform deep-bedded niche systems for these criteria, but that significant overlap occurs in the range of impacts characteristic of high- and low-profitability production between systems. Given the non-optimized status of current deep-bedded niche relative to commodity production, we suggest that optimizing niche systems through improvements in feed and sow herd efficiency holds significant environmental performance improvement potential. Drivers of impacts differed between commodity and deep-bedded niche systems. Feed production was the key consideration in both, but proportionally more important in niche production due to lower feed use efficiencies. Liquid manure management in commodity production strongly influenced GHG emissions, whereas solid manure management increased eutrophication potential due to outdoor storage in deep-bedded niche production. We further observe an interesting but highly imperfect relationship between economic and environmental performance measures, where profitability tracks well with resource (in particular, feed) throughput, but only indirectly with emissions intensity.

1. Introduction

The role of food systems in anthropogenic environmental change is a subject of concern for policy-makers and regulators, the food industry, environmental advocacy groups, and the general public alike. The cumulative contributions of current consumption patterns to resource depletion and waste emission issues (including acid precipitation, ozone depletion, eutrophication, and climate change) are attracting increasing attention. So, too, are the comparative resource and waste emission intensities of alternative food products and food production strategies. Clearly, ensuring the long-term sustainability of local, regional and global food systems requires attention to both scale and efficiency issues. However, appropriate mitigation strategies must be context-sensitive, and be formulated with attention to trade-offs between potentially conflicting social, economic and environmental objectives.

Life cycle assessment is an ISO-standardized biophysical accounting framework used to: (1) characterize the material/energy flows underpinning specific activities and (2) quantify their contributions to resource depletion and emissions-related environmental concerns. This framework is typically not well-suited to the consideration of proximate ecological concerns nor the myriad socio-economic concerns associated with the management of human activities. It does, however, provide a relatively nuanced means of quantifying the requisite resource provisioning and waste assimilatory services upon which they depend, and has a strong history as an eco-efficiency tool.

Pork is currently the most widely consumed meat product, accounting for 37% of meat consumption in developed countries and close to 40% worldwide (FAO, 2006). The United States is the second largest pork producer globally following China, and the second largest exporter after Denmark (FAOstat, 2009). Within the US, a substantial share of pork is produced in the Upper Midwest. Iowa is the leading producer state, accounting for 28% of live-weight production in 2007 (NASS, 2009).

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The majority of contemporary pork production in the Upper Midwest comes from large, high-volume "commodity" farms operating climate-controlled, slatted floor barns and producing over 50,000 pigs annually. A much smaller share of production is contributed by "deep-bedded niche" (henceforth alternately described as "niche") producers using alternative rearing systems. Farmers participating in these production chains typically follow a series of guidelines and protocols as described by Honeyman (2005) and Honeyman et al. (2006). In general producers rear swine in hoop buildings, provide bedding and follow phase-specific space allowance guidelines. The use of farrowing crates, gestation stalls, sub-therapeutic antibiotics, and rendered animal protein is usually avoided. Such operations typically produce, on average, 500–600 pigs per year. Although total deep-bedded niche pork production volumes remain insignificant compared to commodity production, the number of these farms has increased over the last decade. Both researchers and consumers have expressed interest in considerations of environmental performance, animal welfare, food safety, and ownership structure associated with these different pork production strategies (Honeyman et al., 2006).

A number of European researchers have previously applied LCA to evaluate the environmental performance of alternative pork production systems (Zhu and Ierland, 2004; Basset-Mens and van der Werf, 2005; Ericksson et al., 2005; Stern et al., 2005; Williams et al., 2006; Dalgaard et al., 2007). More recently, Lammers and colleagues (2009, 2010) report the direct and embodied energy and greenhouse gas emissions associated with Iowa pork supply chains using conventional versus deep-bedded hoop production facilities. No full LCAs of US pork production technologies have been reported to date.

As pointed out by Lammers and colleagues (2010), US pork production systems are in many ways distinct from European systems, with differences in feeds, housing, and management strategies. Moreover, survey data of costs, profitability and animal performance in the US industry suggest considerable variability within and between US swine production strategies. The objective of the current analysis is therefore to complement and expand upon previous work in the US and elsewhere through the application of ISO-compliant life cycle assessment methods to characterize the cradle-to-farm gate cumulative energy use, ecological footprint, and greenhouse gas and eutrophying emissions associated with commodity and deep-bedded niche pork production systems in the Upper Midwestern United States. In light of intra- and inter-production strategy differences, we further focus on elucidating the comparative performance of low- (LP) and high-profitability (HP) production systems by modeling the most and least profitable (per unit live-weight production) 20% of 80 commodity and niche farms for which we were able to access standardized data. In concert with existing information and performance indicators, this work should contribute to furthering our understanding of a subset of sustainability considerations in pork production in this region, as well as the industry as a whole. It should also provide insights into the relationships between profitability and environmental performance in pork production, and any trade-offs associated with commodity and deep-bedded niche pork production strategies for the environmental variables considered.

2. Methods

Our analysis employs ISO-compliant life cycle assessment methods (ISO, 2006) to characterize the cradle-to-farm gate flows of material and energy inputs, outputs, and a sub-set of the resultant waste emissions associated with conventional and deep-bedded niche swine production strategies in the Upper Midwestern United States. Towards this end, we consider and compare a production system representing contemporary high-volume commodity production norms with a low-volume deep-bedded niche swine production system as described by Honeyman (2005) and Honeyman et al. (2006). Specifically, we quantify the cumulative energy use (MJ), ecological footprint (m^2 of productive ecosystem), greenhouse gas (kg CO_2-equiv.) and eutrophying (g PO_4-equiv.) emissions for piglet production and finishing pigs, and per kg of total live-weight pig production in each system.

3. Life cycle inventory methods, data and assumptions

To account for the variability in economic and biological performance (and attendant environmental consequences) currently achieved within specific production strategies, we characterize production norms for both the most and least profitable (per unit live-weight production) 20% of commodity and niche farms for which we were able to access standardized data. Our estimates of animal performance for deep-bedded niche operations are based on data compiled by Stender and colleagues for the Iowa Pork Industry Center (IPIC, 2009) for 41 Iowa swine farms surveyed in 2006. Our data for animal performance in conventional commodity production systems are derived from 2006 survey data for 39 farms in southern Minnesota as reported in the Farm Financial Database (FINBIN, 2009). Where possible, we build on the research of Iowa commodity pork production systems operating conventional and deep-bedded hoop facilities as reported by Lammers and colleagues (2009, 2010) – particularly with respect to swine diets, and farm-level material and energy use. Remaining data gaps are populated from published literature sources and recommendations provided by swine researchers.

The system boundaries for our analysis encompass the production, processing and transportation of all material and energy inputs to swine feeds, direct in-barn resource flows, and supply chain gaseous and nutrient emissions associated with the live-weight production of slaughter-ready swine at the farm gate. We do not consider the production and maintenance of capital goods, labour inputs or chemotherapeutants (Fig. 1).

4. Commodity production system

The commodity production system we model is representative of approximately 50% of high-volume swine production in the Upper Midwestern United States. Our model assumes a 2400-sow unit producing 40–50,000 weaned pigs annually. Three distinct husbandry phases, each with characteristic diets, housing, and material/energy inputs, are considered. These are a sow gestation phase, a sow farrowing/lactation phase, and a finishing phase. Breeding and gestation occurs in individual stalls, and farrowing/lactation in individual farrowing crates. We assume that weaned pigs are produced and finished on site, where they move directly from weaning to finishing. Finishing pigs are housed in pens inbarns with a maximum capacity of 1200 pigs. Climate-controlled barns with slatted floors are used for all phases (as described in Lammers et al., 2009). It is further assumed that feeds are milled on site.

5. Deep-bedded niche production system

The deep-bedded niche production system we model is characteristic of a very small fraction of swine production in the US Upper Midwest. Our model for deep-bedded niche production similarly comprises a sow gestation phase, a sow lactation phase and a finishing phase. Gestation occurs in bedded group pens with individual feed stalls. Farrowing/lactation takes place in bedded, insulated buildings, with heaters and heat lamps for winter climate control.

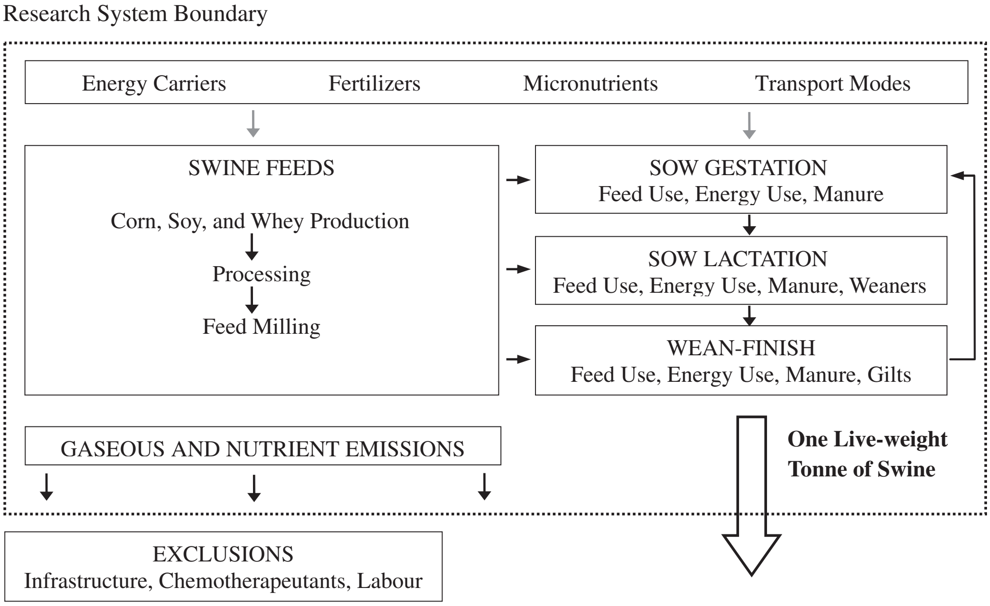

Fig. 1. System boundaries for a cradle-to-farm gate LCA of live-weight swine production in high- and low-profitability commodity and deep-bedded niche production systems in the Upper Midwestern United States (grey font denotes background system data derived from the EcoInvent (2008) database, modified as appropriate to conform to regional conditions).

We assume a 60 sow unit producing roughly 600–650 weaned pigs per year. Finishing pigs are housed in deep-bedded hoop barns with a maximum capacity of 200 pigs.

6. Manure management

In the commodity system, manure is handled as slurry in a central collection pit beneath the finishing barn. Manure volume is calculated based on estimated daily manure excretion rates (ISU, 1995) and cleaning water use (Lammers et al., 2010). For deep-bedded niche production, manure is handled as a solid, and is scraped and stockpiled in windrows within 300 m of the barn. For the purpose of calculating manure handling inputs for deep-bedded niche systems, bedding mass is added. All manure is applied to fields within 5 km of commodity farms and 1 km of the niche farms once yearly. Energy use for transportation and application of manure follows EcoInvent (2008) database processes. For deep-bedded niche production, we assume a 37% mass reduction for stockpiled, unturned manure (prior to spreading) following Tiquia et al. (2002).

Nitrogen and phosphorus emission rates are calculated using a nutrient balance based on feed composition and assuming that 2.42% of swine body mass is nitrogen and 0.55% is phosphorus following Koelsch and Lesoing (1999). Nitrogen excretion estimates are used to calculate direct nitrous oxide, ammonia and nitric oxide emissions from manure management and indirect nitrous oxide emissions from nitrate leaching following IPCC (2006) protocols and relevant Tier I and Tier II emission factors at time of deposition, storage and application. Methane emissions from enteric fermentation and manure management are calculated following IPCC (2006) Tier I protocols (for the emission factors employed in this analysis, see Table S1).

7. Feed input production and processing

We assume the use of the same feeds (Lammers and Colleagues, 2008) for commodity and deep-bedded niche production (Tables S2 and S3). Feed input models and data follow those described in Pelletier et al. (2010). Inventory data for soy and corn-based feed inputs are derived from US National Agricultural Statistics Service (NASS) publications, Iowa State University extension publications and peer-reviewed literature. Yields are based on 5-year averages for 2003–2007 calculated from NASS data. Fertilizer mixes correspond to average US consumption as reported by NASS. Application rates of pesticides and fertilizers used in soy and corn production are based on 2005 NASS data for Iowa. Energy inputs are based on Iowa averages for 2001 (detailed inventory data provided in Table S4). Field-level ammonia, nitrous oxide, nitric oxide, nitrate and carbon dioxide (from urea fertilizers) emissions are calculated following IPCC (2006) Tier 1 protocols using relevant default emission factors. A 2.9% surplus phosphate emission rate is assumed following Dalgaard et al. (2008). All fertilizers and pesticides are assumed to be transported 1000 km by truck, and all seed inputs 100 km by truck. Both corn and soy are produced in high volumes in this region. Soy beans are assumed to be transported 100 km by truck to processors, and 100 km to farms. Corn is assumed to be transported 30 km to farms, reflecting the higher volume of corn production in Iowa. Processing of soy beans into meal and oil applies inventory data reported by Schmidt (2007), adjusted to reflect the US electricity mix (Table S5). Energy use for in-barn feed mixing, milling and distribution follows Lammers et al. (2010).

To characterize whey production, inventory data for milk production are derived from Arsenault et al. (2009) and milk processing from Feitz et al. (2007). Inventory data for DL-methionine production reported by Binder (2003) are assumed to be representative of all synthetic amino acids used in the modeled swine feeds. Mineral input models are derived from the EcoInvent (2008) database.

8. In-barn material and energy use

Direct in-barn material and energy use associated with climate control, lighting, feed distribution and cleaning in conventional and deep-bedded hoop swine production facilities in Iowa has previously been characterized by Lammers and colleagues (2009,2010). Our models draw directly on this work, modifying specific data points as appropriate to conform to the model assumptions of the present analysis. For bedding use in the deep-bedded niche systems, we assume the use of corn-stalks. Since these are returned to the fields after use, we account for the collection and transportation of bedding between fields and farms, but not for agricultural production following Lammers et al. (2010).

9. Co-product allocation

Co-product allocation is required to apportion resource use and emissions between the products of multi-output systems. Since the purpose of the present analysis is to describe the biophysical environmental dimensions of a food production system, it is appropriate to base allocation decisions on an inherent biophysical characteristic of co-products which both reflects the efficiency of the process and is relevant to the underlying causal impetus of the production system. To this end, the gross chemical energy content of co-product streams will be used as the basis for all allocation decisions because: (1) producing caloric energy is the root driver of all food production activities and (2) the chemical energy of food products present in raw materials is apportioned between processed outputs in a quantifiable manner which speaks directly to the ecological efficiency with which the system provides available food energy. For a detailed discussion of this rationale, see Ayer et al. (2007) and Pelletier and Tyedmers (2007). For the present analysis, allocation is required for soy bean processing and whey production only.

10. Life cycle impact assessment

Impact assessment in LCA involves calculating the contributions made by the material and energy inputs and outputs tabulated in the inventory phase to a specified suite of environmental impact categories. We consider two resource use impact categories (energy use and ecological footprint) and two emissions-related categories (greenhouse gas emissions and eutrophying emissions). All impacts are calculated using the SimaPro 7.1 LCA software package from PRé Consultants (PRe, 2008). Energy use (MJ) is quantified following the Cumulative Energy Demand method (Frischknecht et al., 2003), which accounts for conversion efficiencies and the quality of energy inputs. The ecological footprint, which quantifies the area of productive global ecosystem required to furnish the material and energy resources and sequester the greenhouse gas emissions associated with a product or service (in m^2 of productive ecosystem) is calculated following the EcoInvent 2.0 method (EcoInvent, 2008). This method is modified to include methane and nitrous oxide emissions. We believe this indicator to be more relevant than simple measures of land-use, which typically reflect occupation only rather than the quality of land-use and its relation to biocapacity considerations. Greenhouse gas emissions (CO_2-equiv.) (assuming a 100-year time horizon) and eutrophying emissions (PO_4^-equiv.) are quantified following the CML 2001 method (Guinee et al., 2001). These assessment methods follow the problem-oriented mid-point approach, meaning that results are expressed in terms of total resource use and emissions rather than measured impact levels.

11. Life cycle interpretation

Impacts are calculated for producing individual piglets and finished pigs in each system, as well as per kg of total live-weight production. Cradle-to-farm gate supply chain impacts are assessed to identify impact hotspots and key leverage points for environmental performance improvements. Comparative impacts between production systems are evaluated and relationships to profitability are assessed.

We also assess the energy return on investment (EROI) ratios in commodity and deep-bedded niche swine production systems in order to estimate the ecological efficiency with which these competing swine production technologies provide valued outputs from a variety of perspectives. Specifically, we evaluate: (a) the amount of human-edible food energy produced relative to the total industrial energy inputs required (an anthropocentric perspective on non-renewable resource use efficiency); (b) the amount of human-edible food energy produced relative to the amount of human-edible food energy consumed by the swine (an anthropocentric perspective on renewable resource use efficiency); and (c) the amount of gross chemical energy produced relative to the gross energy consumption of swine in each scenario (an ecological perspective on renewable resource use efficiency).

12. Results

12.1. Life cycle inventory results

Feed use is consistently higher for low-profitability (LP) compared to high-profitability (HP) systems for both commodity and deep-bedded niche production, with the exception of lactation feed use in the commodity systems. It is also consistently higher for deep-bedded niche production, with no overlap between HP niche and LP commodity systems in any of the phases considered. Our life cycle inventory analysis further suggests larger differences in feed consumption between high- and low-profitability niche swine production systems than are seen within commodity systems (Tables S6 and S7). As a result, since feed composition is the same between commodity and deep-bedded niche systems, estimates of protein, nitrogen and phosphorus intake are correspondingly higher for deep-bedded niche systems (Table S8).

Performance data for commodity and niche gestating and lactating sows suggest distinct differences related to respective production strategies. Annual output of piglets is much higher from commodity systems because sows have more litters, the weaning time is shorter, and piglets are weaned at lower weights. Sow weight gain and weight at replacement is also lower in the commodity systems. The highest mortality and replacement rate is seen in the LP commodity systems. For most variables considered, there is less difference between high- and low-profitability niche systems compared to commodity systems for the gestation and lactation phases (Table 1).

Deep-bedded niche pigs finish at slightly higher weights than commodity pigs, and have substantially longer finishing times. Feed:gain ratios for deep-bedded niche production are notably higher, with HP niche production evincing a feed:gain ratio 31% higher than that observed in LP commodity production and 49% higher than HP commodity production. Mortality in HP niche production is close to that of HP commodity production (Table 2).

With respect to farm-level material and energy inputs, the distinct differences between commodity and deep-bedded niche herds reflect differences in housing strategies; for example the use of cleaning water for commodity production compared to bedding for niche production, or greater energy inputs in the commodity system for climate control (Tables 3–5).

12.2. Life cycle impact assessment results

The attribution of life cycle impacts to specific aspects of producing weaned pigs (i.e. feed production, in-barn energy use, manure management, etc.) vary with impact category. For commodity production, in-barn energy use is the most important consideration for cumulative energy use, whereas GHG and eutrophying emissions are most strongly associated with manure management.

Table 1
Performance of gestating and lactating sows in high- and low-profitability commodity and deep-bedded niche sow herds in the Upper Midwestern United States. All data from Stender et al. (IPIC, 2009) for niche sows and FINBIN (2009) for commodity sows unless otherwise noted.

Performance criteria	Commodity (HP)	Commodity (LP)	Niche (HP)	Niche (LP)
Starting weight[a] (kg)	118.8	110.5	126.0	123.7
Annual gain (kg)	27.2[b]	41.1[b]	53.6	57.7
Litters/year	2.2	1.97	1.6	1.6
Piglets weaned/year	21.32	16.94	10.9	10.2
Weaner weight (kg)	6.8	6.4	15.9	12.7
Weaning time (days)	21	21	42	42
Sow mortality (%)	4.9	13.4	4.9	6.8
Replacement rate (%)	38.3[c]	77.8[c]	63.8	65.9
Weight at slaughter (kg)	204.5	170.5	238.6	215.9

[a] Replacements assumed to be derived from same production system.
[b] Calculated.
[c] PigChamp (2006).

Table 2
Performance of finishing pigs in high- and low-profitability commodity and deep-bedded niche swine herds in the Upper Midwestern United States. All data from Stender et al. (IPIC, 2009) for niche herds, data for commodity herds from FINBIN (2009) unless otherwise noted.

Performance criteria	Commodity (HP)	Commodity (LP)	Niche (HP)	Niche (LP)
Starting weight (kg)	6.8	6.4	15.9	12.7
Finishing weight (kg)	118.8	110.5	126.0	123.7
Total gain (kg)	112.0	104.1	110.1	111.0
Feed:gain ratio	2.44	2.77	3.63	3.96
Mortality (%)	6.7	9.2	7.8	13.7
Finishing time (days)	130	141	192	203
Cycles per year[a]	2.70	2.50	1.85	1.75

[a] Calculated. Includes 5 day turn-around between cycles.

Table 3
Material and energy inputs/output associated with the maintenance of gestating sows in high- and low-profitability commodity and deep-bedded niche sow herds in the Upper Midwestern United States.

INPUTS	Commodity (HP)	Commodity (LP)	Niche (HP)	Niche (LP)
Feed per sow[a] (kg/head/day)	2.27	2.27	2.61	4.19
Drinking water[b] (l/head/day)	16.0	16.0	16.0	16.0
Cooling/cleaning water[b] (l/space/year)	138	138	0	0
Energy[b] (MJ/space/year)				
Electricity	201.1	201.1	39.9	39.9
Liquid propane gas	497.5	497.5	0	0
Diesel	45.1	45.1	69.3	69.3
Cornstalk Bedding[c] (kg/space/year)	0	0	730	730
OUPUTS				
Manure [d]				
Commodity (litres/head/day)	6.1	6.1		
Niche (kg/head/day)			6.9	6.9

[a] Stender et al. (IPIC, 2009) for niche and FINBIN (2009) for commodity.
[b] Calculated as per Lammers et al. (2010).
[c] Harmon et al. (2004).
[d] ISU (1995). Cleaning water is added to reported commodity manure production volume for calculating inputs to manure management, whereas bedding is added to reported niche manure production mass.

Table 4
Material and energy inputs/output associated with the maintenance of lactating sows in high- and low-profitability commodity and deep-bedded niche sow herds in the Upper Midwestern United States.

INPUTS	Commodity (HP)	Commodity (LP)	Niche (HP)	Niche (LP)
Feed per sow[a] (kg/head/day)	5.19	5.14	4.28	6.34
Drinking water[b] (l/head+litter/day)	35	35	35	35
Cooling/cleaning water[b] (l/space/year)	1143	1143	0	0
Energy[b] (MJ/space/year)				
Electricity	3198.0	3198.0	105.3[c]	105.3[c]
Liquid propane gas	1359.4	1359.4	0	0
Diesel	278.6	278.6	52.6[c]	52.6[c]
Cornstalk bedding (kg/space/year)	0	0	730	730
OUPUTS				
Manure[d] (litres/head+litter/day)				
Commodity (litres/head/day)	13.2	13.2		
Niche (kg/head/day)			15.3	15.3

[a] Stender et al. (IPIC, 2009) for niche and FINBIN (2009) for commodity.
[b] Calculated as per Lammers et al. (2010).
[c] Energy inputs for niche lactating sows are expressed per litter rather than per space/year.
[d] ISU (1995) Cleaning water is added to reported commodity manure production volume for calculating inputs to manure management, whereas bedding is added to reported niche manure production mass.

Table 5
Material and energy inputs/output associated with the maintenance of finishing pigs in high and low performing commodity and deep-bedded niche swine herds in the Upper Midwestern United States.

INPUTS	Commodity (HP)	Commodity (LP)	Niche (HP)	Niche (LP)
Feed per pig[a] (kg/head/day)	2.17	2.14	2.22	2.34
Drinking water[b] (l/head/day)	10	10	10	10
Cooling/cleaning water[b] (l/space/year)	137	137	0	0
Energy[b] (MJ/space/year)				
Electricity	86.8	86.8	6.5	6.5
Liquid propane gas	225.7	225.7	0	0
Diesel	51.1	51.1	20.8	20.8
Cornstalk bedding[c] (kg/head)	0	0	91	91
OUPUTS				
Manure[d]				
Commodity (litres/head/day)	5.30	5.30		
Niche (kg/head/day)			5.0	5.0

[a] Stender et al. (IPIC, 2009) for nice and FINBIN (2009) for commodity.
[b] Calculated as per Lammers et al. (2010).
[c] Brumm et al. (2004).
[d] ISU (1995) Cleaning water is added to reported commodity manure production volume for calculating inputs to manure management, whereas bedding is added to reported niche manure production mass.

Feed production is the dominant contributor to the ecological footprint of producing weaned pigs in the commodity system. In contrast, feed production is the most important contributor to all categories other than eutrophying emissions (manure management) in the production of weaned pigs in the deep-bedded niche system. High-profitability operations have consistently lower impacts compared to low-profitability operations for both commodity and deep-bedded niche piglet production (Fig. 2 – for a breakdown of percent contributions, see Table S9). On average,

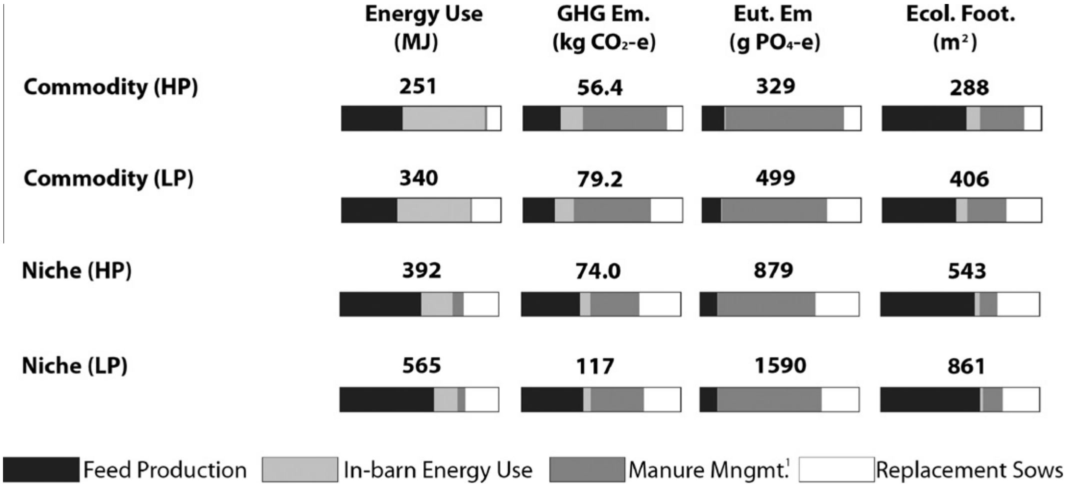

Fig. 2. Cradle-to-farm-gate life cycle cumulative energy use (MJ), ecological footprint (area of productive ecosystem), and greenhouse gas (CO_2-equiv.) and eutrophying (PO_4-equiv.) emissions per weaned pig produced for finishing in high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States. ([1]Manure management includes bedding for deep-bedded niche systems.)

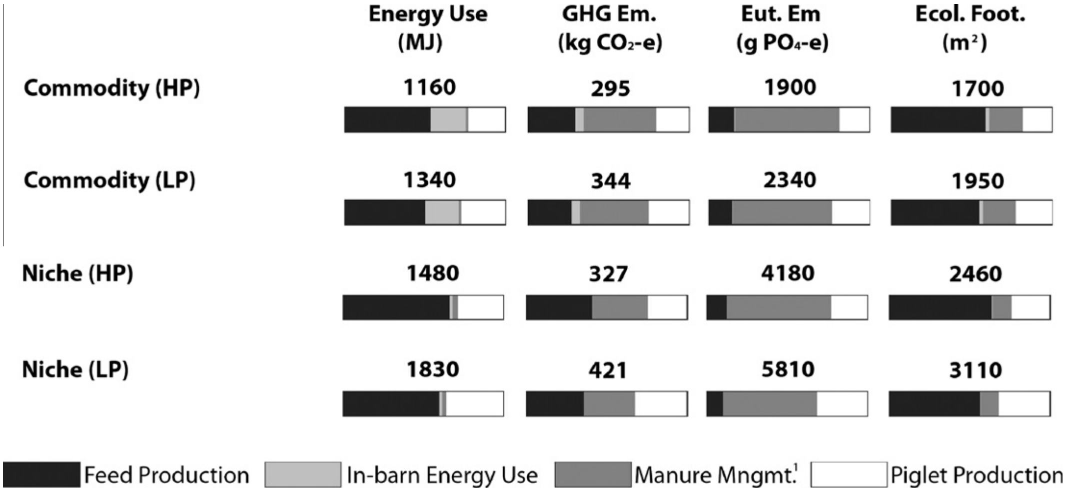

Fig. 3. Cradle-to-farm-gate life cycle cumulative energy use (MJ), ecological footprint (area of productive ecosystem), and greenhouse gas (CO_2-equiv.) and eutrophying (PO_4-equiv.) emissions per finished pig in high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States. ([1]Manure management includes bedding for deep-bedded niche systems.)

HP commodity systems have 70% of the impacts associated with LP commodity systems versus 63% for high compared to low-profitability deep-bedded niche systems for the production of weaned piglets. HP deep-bedded niche systems have higher energy use, euthrophying emissions and ecological footprint than LP commodity systems, but fall between high- and low-profitability commodity systems in terms of GHG emissions. Overall, impacts per weaned pig produced are 86% higher for niche production, although it is important to note that niche weaners are heavier (Fig. 2).

The life cycle cumulative energy use and ecological footprint associated with finishing pigs are more strongly tied to feed production in the commodity system, whereas manure management is the largest contributor to greenhouse gas (75% of this from manure methane emissions during pit storage, and the balance from manure nitrous oxide emissions at application) and eutrophying emissions (Fig. 3 – for a breakdown of percent contributions, see Table S10). For the deep-bedded niche system, feed production is the most important consideration for all categories other than eutrophying emissions, where manure management is the primary factor. Producing weaned pigs contributes strongly to all impact categories in both the commodity and niche systems, accounting for approximately 20–40% of impacts across systems and categories (Fig. 3). Again, impacts are consistently higher for low-profitability compared to high-profitability production, and the best-performing deep-bedded niche systems have higher energy use, eutrophying emissions and ecological footprint compared to the low-profitability commodity systems, but lower GHG emissions (Fig. 3). Within commodity systems, high-profitability production averages 85% of the impacts attributable to low-profitability production on a whole-animal basis. For deep-bedded niche production, high-profitability production averages 77% of the impacts of low-profitability production.

Per live-weight kg of finished pig produced, impacts are consistently lowest for HP commodity production. Since deep-bedded niche pigs are marketed at higher weights than commodity pigs, a slightly different pattern of impacts is observed when assessed on a live-weight basis compared to a whole-animal basis. Here, both greenhouse gas emissions and energy use in HP deep-bedded niche production fall between the values estimated for high- and low-profitability commodity production. Eutrophying emissions and ecological footprint remain higher, however (Table 6). On

Table 6
Cradle-to-farm gate cumulative energy use, ecological footprint, and greenhouse gas and eutrophying emissions associated with live-weight pork production in high- and low-profitability commodity and deep-bedded niche pig production systems in the Upper Midwestern United States.

	Energy use (MJ/kg)	Ecol. footprint (m^2/kg)	GHG emissions (kg CO_2-equiv./kg)	Eutrophying emissions (g PO_4-equiv./kg)
Commodity (HP)	9.7	14.2	2.47	15.9
Commodity (LP)	11.9	17.3	3.05	20.8
Niche (HP)	11.4	18.9	2.52	32.2
Niche (LP)	14.4	24.6	3.33	45.9

Table 7
Energy return on investment (EROI) ratios for high- and low-profitability commodity and deep-bedded niche pork production in the Upper Midwestern United States as: (a) human edible caloric energy return on industrial energy investment, (b) human edible caloric energy return on human edible caloric energy investment, and (c) gross chemical energy return on gross chemical energy investment.

EROI	Industrial energy[a] (%)	Human edible energy[a] (%)	Gross chemical energy[b] (%)
Commodity (HP)	26.7	7.4	13.1
Commodity (LP)	21.8	6.3	11.3
Niche (HP)	22.7	4.8	8.5
Niche (LP)	18.0	3.7	6.7

[a] Assumes 56% yield of boneless meat per live-weight kg produced and an energy density of 4.63 MJ/kg of raw, boneless pork.

[b] Assumes a whole-animal energy density of 4.63 MJ/kg.

average, there are larger differences in impact levels between high- and low-profitability deep-bedded niche systems (25%) compared to high- and low-profitability commodity systems (20%). The most profitable commodity systems produce live-weight pork with 77% of the average impacts associated with equivalent production in the most profitable deep-bedded niche systems. Differences are largest for eutrophying emissions (50%) and ecological footprint (25%), but quite small for energy use (15%) and GHG emissions (2%) (Table 6).

Energy returns on investment (EROI) for industrial and biotic (as measured in gross chemical energy) energy consumed in swine production were consistently greater for high-profitability compared to low-profitability systems (Table 7). Commodity systems similarly evinced higher returns, except where high-profitability niche production generated slightly higher energy returns on industrial energy investment compared to low-profitability commodity production. Congruent with observed patterns in cumulative energy use, human edible energy returns on industrial energy investment were greatest for HP commodity production (26.7%) and least for LP niche production (18.0%). Due to the fact that swine diets consist largely of human-edible products (corn and soymeal), human edible energy returns on edible energy investment ratios were quite low, ranging from 7.4% to 3.7%. Gross chemical energy return relative to gross chemical energy consumed by the swine varied between 13.1% and 6.7% (Table 7).

13. Discussion

Our analysis of the comparative life cycle impacts of high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States points to a range of important considerations and nuances in describing and seeking to further ecological efficiency objectives in this industry. Of first order interest is that, according to the suite of biophysical environmental performance measures considered, the most profitable contemporary commodity production systems consistently outperform deep-bedded niche production systems in this region. However, the degree of difference in performance within and between production strategies varies widely. There is substantial overlap between commodity and deep-bedded niche systems in terms of GHG emissions and energy use, but no overlap for ecological footprint or eutrophying emission per live-weight kg produced. In some instances, such as greenhouse gas emissions, differences are so small as to be attributable to analytical uncertainties. In others, such as eutrophying emissions, the differences are substantial and clearly linked to characteristic management strategies.

It is also essential to note that, whereas the commodity systems evaluated operate at levels of efficiency in part attributable to historical subsidies in the form of extensive research and education which have served to optimize commodity pork production, the deep-bedded niche systems represent a relatively recent move to alternative production strategies and have not been similarly optimized (The IPIC data set collected by Stender and colleagues (2009) and used in this analysis represents the first large-scale effort to analyze efficiencies in niche pork production in this region). This is certainly evident in the much larger differences in impacts between high- and low-profitability deep-bedded niche systems compared to high- and low-profitability commodity systems. We therefore caution against interpreting our results as speaking definitively to the potential comparative efficiencies of these production technologies. Rather, they usefully inform considerations of current comparative performance and point towards important improvement opportunities for both commodity and deep-bedded niche production.

Also important to consider are the different *drivers* of ecological efficiencies (i.e. resource or emissions intensity per unit production) in commodity versus deep-bedded niche swine production. At a systems-level, one such obvious difference is the much higher feed efficiency attained in commodity production, which has a critical influence on all impact categories of concern. The much higher productivity of commodity sow herds, which produce twice the number of weaned pigs with lower feed inputs relative to the deep-bedded niche systems, is also important. HP niche piglets have, on average, 86% higher impacts than HP commodity weaners. For this reason, whereas the contribution of producing weaned pigs is roughly 20–25% of average impacts in commodity production, it contributes 25–30% of average impacts in deep-bedded niche production. Improving swine herd productivity is thus a key leverage point for improving the ecological efficiency of deep-bedded niche pork production as a whole. A possible alternative would be to source weaners from commodity systems for niche finishing in deep-bedded hoop buildings – particularly in summer, where feed diversion for thermoregulation in hoop production is not an issue. However, animal welfare trade-offs must be considered. Also of critical importance are differences in manure management strategies. Finally, mortality rates are seemingly high in both commodity (6.7–9.2%) and deep-bedded niche (7.8–13.7%) production. Reducing mortality rates might thus be an effective means of improving feed use efficiencies and reducing related impacts in both systems. The implications of these differences for each impact category are explored in detail below.

13.1. Energy use

Feed production is the largest contributor to energy use per live-weight output in both commodity and deep-bedded niche production systems. Certainly, this is consistent with observations from LCA research of swine production elsewhere (Zhu and van

Ierland, 2004; Basset-Mens and van der Werf, 2005; Ericksson et al., 2005; Stern et al., 2005; Williams et al., 2006; Dalgaard et al., 2007), and also from comparable work of animal husbandry generally (Pelletier, 2008; Pelletier et al., 2010). Notable, too, is that feed is proportionally more important in deep-bedded niche production compared to commodity production. This reflects the much lower feed efficiencies currently achieved in the deep-bedded niche systems (45% higher feed use per kg live-weight production for HP niche compared to HP commodity and 90% higher for low-profitability niche).

We did observe that in-barn energy use is slightly higher for commodity weaner production (18%) compared to niche, despite that twice as many weaners are produced and that the commodity weaners are lighter. Overall energy use, however, was higher for deep-bedded niche systems due to higher feed use and the energy costs of replacement sows.

Of particular interest here is that, although overall life cycle energy use is higher for deep-bedded niche finishing, in-barn energy use is a fraction of that observed in commodity finishing. Specifically, in-barn cumulative energy use for commodity finishing (largely for climate control) is more than eight times that consumed in deep-bedded niche production – an observation supported by the work of Lammers et al. (2010), who reported lower energy use in deep-bedded hoop housing for swine finishing in Iowa. This underscores that, by investing in climate control, commodity producers effectively substitute industrial energy for feed energy. In contrast, since deep-bedded niche pigs must devote a fraction of feed energy to maintaining body temperature (particularly in winter), greater feed throughput is necessary, with cascading effects for all impact categories considered. This observation is consistent with that of Honeyman and Harmon (2003), who observed lower feed efficiencies for winter compared to summer deep-bedded hoop-raised pigs. However, there are certainly other forces at work in determining feed efficiency, including genetics, feeder style/adjustment/location/condition, particle size, losses, etc. For this reason, further research would be necessary to ascertain the extent to which the observed differences are attributable to climate control strategies.

13.2. Greenhouse gas emissions

The factors determining supply chain greenhouse gas emissions are distinctly different between commodity and deep-bedded niche production. In commodity systems, manure management is the primary factor, in particular the substantial methane emissions associated with the liquid manure system. This points to the importance of considering technological mitigation strategies such as anaerobic digesters in commodity production, or the trade-offs associated with solid manure management strategies. Although overall GHG emissions are slightly higher in HP niche compared to HP commodity production, manure-related emissions are higher for commodity production.

In contrast, feed production is the most important contributor to life cycle greenhouse gas emissions in deep-bedded niche production, followed by (and directly influencing) manure management-related emissions (i.e. greater feed throughput means greater manure production and associated manure nitrous oxide emissions – the most important component of manure-related emissions for niche production). Improved feed efficiency, as well as improved swine herd productivity, thus represent the most important leverage points for reducing greenhouse gas emissions in deep-bedded niche production systems. This might be achieved by several means, including the identification of optimal diets for niche production, targeted use of climate control, and better feed management to minimize waste and improve conversion efficiency.

13.3. Eutrophying emissions

The higher eutrophication potential we observed for deep-bedded niche production is partially attributable to higher feed throughput, nutrient excretion, and associated nutrient losses during manure storage and application – again pointing to the desirability of further research to optimize niche diets. However, the primary driver here is differences in manure management strategy. Although liquid manure management in commodity systems is disadvantageous with respect to greenhouse gas emissions, the use of pit storage offers considerable advantage over the windrow storage of solid manure in deep-bedded niche systems for eutrophying emissions. Exposure to the elements during storage is a key vector for nutrient loss. This is a non-trivial consideration, particularly given that nutrient run-off from agriculture in the US is a known contributor to significant eutrophication problems in the Gulf of Mexico (Rabalais et al., 2002; Diaz and Rosenberg, 2008). One potentially efficacious mitigation strategy is the use of covered manure storage facilities for deep-bedded niche swine production.

Although our models assumed similar eutrophication potential per unit nutrient at time of application, it should be noted that application strategy may also be important. Injection of liquid manure from commodity systems would likely reduce eutrophying emissions compared to surface application of solid manure. In contrast, surface application of liquid manure would have greater eutrophication potential than if solid manure were surface applied and incorporated. The influence of such considerations on life cycle eutrophication potential for commodity and deep-bedded niche swine production merits further research.

13.4. Ecological footprint

The ecological footprint metric is unique among impact assessment methods available for use in LCA in that it facilitates a direct measure of the comparative biocapacity required to support the provision of a good or service. It does so by aggregating the area of productive ecosystem (an ultimately limited resource) required to both supply the material/energy inputs and assimilate a fraction of the wastes (the GHG emissions) associated with specific products, services, or levels of consumption (Rees and Wackernagel, 1994). Not surprisingly, feed use was the primary contributor to the ecological footprint of both commodity and deep-bedded niche swine production. This insight alone is important, pointing as it does to the fact that many of the key determinants of environmental performance in swine production occur not on the farm itself but rather far upstream along industrial feed provision chains – hence the importance of the life cycle perspective to environmental management in this industry. However, the area of productive ecosystem required to assimilate associated greenhouse gas emissions was also important – making visible the macroscale waste sink requirements associated with swine production which are neither apparent at the level of production nor currently reflected in the cost structure of the swine industry.

13.5. Profitability and ecological efficiency

Also of great interest is the relationship between profitability (i.e. economic efficiency) and ecological efficiency. We observed that impacts were consistently higher in low-profitability production systems. Certainly, this is intuitive to the extent that profits are determined by input costs such as feed and industrial energy. Feed costs for deep-bedded niche finishing were \$0.47 (HP) and \$0.62 (LP)/live-weight kg produced, whereas for commodity finishing they were \$0.36 (HP) – \$0.46 (LP) (FINBIN, 2009; IPIC, 2009). All else being equal, systems that maximize productivity returns on resource investments are clearly desirable. However, all else is rarely equal. Both the qualities and quantities of resource throughput may vary, along with associated waste emissions – with the latter considerations currently excluded from price determination. This means that current production systems effectively externalize important environmental costs. The very similar market prices per unit live-weight production within and between HP and LP commodity and deep-bedded niche systems (IPIC, 2009, FINBIN, 2009) bears ample testament. Moreover, trade-offs are often inevitable when we seek to optimize multiple criteria. Certainly this is true in the case of identifying best management practices for manure handling, with liquid manure exacerbating greenhouse gas emissions whilst reducing eutrophying emissions relative to solid manure management. Interestingly, we observed that the most profitable deep-bedded niche operations produced, on average, half of the pork produced in the least profitable operations (IPIC, 2009). It would thus appear that both economic and environmental performance is superior in small versus larger deep-bedded niche operations, which challenges standard assumptions regarding economies of scale.

In light of the growing magnitude of human activities relative to resource and waste sink availability, we believe that such biophysically-based returns on investment considerations need be increasingly considered in policy and management decisions. With attention to trade-offs, such considerations can help inform the identification and preferential promotion of productive strategies which maximize our capacity to meet specific objectives whilst minimizing resource and emissions intensities. However, it must be remembered that efficiencies can be considered from a variety of perspectives, and that both anthropocentric and ecocentric objectives must be weighed.

Clearly, growing concerns regarding both the availability and environment costs of non-renewable energy resources underscore the important of maximizing industrial energy returns on investment. We found that such returns varied from as low as 18% (LP niche) to as high as 25% (HP commodity), but that the difference between high performing niche and commodity systems were not substantial.

Also meriting consideration are returns on edible food energy investment. Globally, the livestock industry currently consumes roughly one third of cereal crops, with pork production accounting for a large fraction (Steinfeld et al., 2006). In light of the projected doubling of meat production by 2050 to meet the demands of a growing population consuming diets higher in animal products, questions regarding optimal use of edible foodstuffs will necessarily gain increasing currency. We found returns on investment of 3.7–7.4%. This is less than comparable returns for grass-finished beef reported by Pelletier et al. (2010), but higher than for grain-finished beef.

While both of the prior EROI concerns are primarily anthropocentric, considering resource use from an ecological perspective is also important. Krausmann et al. (2008) estimate that 58% of human-appropriated, directly used biomass flows are currently channeled through global livestock systems. This has obvious implications for energy flows through ecosystems, and their capacity to support biodiversity (Imhoff et al., 2004). We found a gross chemical energy return on investment of 6.7–13.1% for the swine production systems considered – much higher than comparable returns for beef production (Pelletier et al., 2010) but lower than would be anticipated for poultry production, where feed efficiencies are higher (Pelletier, 2008).

14. Conclusions

It is clear that both substantial differences and overlap occur within and between commodity and deep-bedded niche swine production strategies for the suite of environmental issues considered in this analysis. Opportunities exist for performance improvements in both systems – as evidenced by the wide range of performance within both commodity and niche production systems, as well as differences in management strategies giving rise to the characteristic life cycle environmental profiles of these systems.

For deep-bedded niche systems, improving swine herd productivity and feed efficiencies, and reducing nutrient losses from manure storage are critical. Research towards optimizing diet formulation for niche production is also needed. The genetics of pigs grown in niche systems are different from commodity systems, hence diets should be formulated to match their genetic potential. In particular, identifying the appropriate balance of amino acids to energy consumed will be important, since niche pigs devote more feed energy to thermoregulation than do commodity pigs raised in climate-controlled buildings. This would serve to reduce N emissions from niche production. The use of more fibrous feed may also be potentially efficacious in this respect, both because pigs on high-fiber diets produce more body heat, and because fibrous feedstuffs encourage a shift in excreted nitrogen towards more stable forms.

Greenhouse gas emissions in commodity production may be much reduced through solid manure management or the use of methane digesters. However, mitigation strategies must clearly be sensitive to trade-offs along different dimensions of environmental performance. While profitability in swine production appears to be inversely proportional to feed-related environmental impacts, it is clear that many important negative externalities remain – in particular, greenhouse gas and eutrophying emissions, and the requisite ecosystem support services required to both provide material and energy inputs and assimilate the associated wastes. Here, policy intervention may be essential to preferentially promote environmentally superior management practices.

We should note that our focus on comparative ecological efficiencies provides a sound basis for identifying improvement opportunities in these systems but does not address the issue of sustainable scale (i.e. absolute impacts relative to the carrying capacity of host ecosystems). Nor have issues of animal welfare been considered. While beyond the scope of the present analysis, such considerations need necessarily be weighed carefully in policy and management decisions that influence industry structure and direction.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agsy.2010.07.001.

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