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Can the environmental impact of pig systems be reduced by utilising co-products as feed?

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ABSTRACT

The implications of using co-products from the supply chains of human food and biofuels in pig diets for the environmental impacts of Canadian pig systems were examined using Life Cycle Assessment. The functional unit was 1 kg expected carcass weight (ECW) and environmental impacts were calculated as: Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Nonrenewable Energy Use (NRE) and Nonrenewable Resource Use (NRRU). Maximum inclusion limits which would not negatively affect animal performance were defined for: meat meal (55), bakery meal (87), corn DDGS (261) and wheat shorts (291) (numbers in brackets represent average across all feeding phases in g/kg as fed). Nutritionally equivalent grower/finisher (G/F) diets containing maximum inclusions of these co-products were formulated individually. These diets were compared to a simple control diet based on corn and soya meal using 1000 parallel Monte-Carlo simulations. The maximum inclusion of meat meal reduced NRRU and NRE per kg ECW by 9% and 8% compared to the control ($P < 0.001$), EP and AP increased by 10% and 7% ($P < 0.001$), with no significant change in GWP. Maximum inclusion of bakery meal was found to reduce all environmental impacts for all categories modelled by <5% ($P < 0.001$). Maximum inclusion of corn DDGS in the G/F diets resulted in relatively large increases in NRRU (56%), NRE (48%) and GWP (16%) (all $P < 0.001$). The maximum corn DDGS diet caused a mean reduction of <1% in AP ($P = 0.01$) and did not significantly alter EP. Maximum inclusion of wheat shorts reduced GWP, NRE and NRRE by >10% ($P < 0.001$) but did not significantly alter EP or AP. The environmental impact implications for pig farming systems of high inclusion levels of co-products in G/F diets formulated for economic goals (i.e. least cost per kg live weight gain), were also modelled for the first time. Four further G/F diets were formulated on a least cost basis at 100%, 97.5%, 95% and 92.5% of the energy density required for maximum feed efficiency. Minimum nutrient to net energy ratios were defined in the formulation rules to ensure the first limiting resource of all diets for growth was energy. The least energy dense diet contained the highest level of co-products (294 g/kg as fed) and the most energy dense diet contained the least (108 g/kg as fed). The least energy dense diet reduced NRE and NRRU by 9% ($P < 0.001$) and GWP by 4% ($P = 0.018$) when compared to the diet designed for maximum feed efficiency, but increased AP and EP by <1% ($P < 0.001$). The other two intermediate levels of energy density followed the same pattern but the effects were not linear. The increased inclusion of co-products in G/F diets formulated for economic goals can produce environmental impact reductions for some environmental impact categories in pig farming systems.

1. Introduction

The environmental impacts of livestock systems have come under increased scrutiny in recent years (Steinfeld et al., 2006), resulting in greater focus on identifying and mitigating their environmental burdens. Previous Life Cycle Assessment (LCA) studies have shown that feed production causes the majority of Global Warming Potential (GWP) (Basset-Mens and Van Der Werf, 2005; Macleod et al., 2013; Reckmann et al., 2013), Nonrenewable Energy (NRE) and Nonrenewable Resource Use (NRRU) (Mackenzie et al., 2015) resulting from pig farming systems. The majority of Acidification Potential (AP) and Eutrophication Potential (EP)

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caused by pig farming systems is due to emissions during manure storage and application, a direct result of the excretion of N and P by the animal (Basset-Mens and Van Der Werf, 2005; Dourmad et al., 2014; Reckmann et al., 2013). As such the ingredient and nutritional composition of the diets in pig farming systems are extremely important considerations when quantifying their environmental impacts. Due to the pressure of the animal feed supply chain on human food systems (Steinfeld et al., 2006), there is an increased interest in the use of alternative feed ingredients (co-products) in livestock diets (Woyengo et al., 2014; Zijlstra and Beltranena, 2013). However, the consequences of including of such co-products in pig diets for the environmental impacts of the system have not previously been investigated systematically.

Commercial pig diets are usually formulated for economic objectives (Ferguson, 2014). There are various economic objectives for which pig diets may be formulated; one of the most common is to minimise the cost of feed per kg live weight (LW) gain (ABN, 2014). Energy is the most expensive component of pig diets (Velayudhan et al., 2015). When formulating commercial diets optimum nutrient to energy ratios can be defined to ensure energy is the first limiting resource of the diet for animal growth. As feed prices vary, the optimal feeding strategy to minimise the cost of feed per kg LW gain will also fluctuate. When ingredient prices are relatively low, achieving optimum feed efficiency is less important when trying to minimise cost/kg LW and the optimal solution may be diets of lower energy density (Saddoris-Clemons et al., 2011). Diets with lower energy density tend to cost less per tonne due to greater inclusions of low value co-products, such as wheat shorts or dried distillers grains with solubles (DDGS).

The first aim of this study was to use LCA modelling to investigate the effect of including specific co-products in grower/finisher (G/F) diets on the environmental impact of Canadian pig systems. The co-products investigated were meat (pork) meal, bakery meal, corn DDGS and wheat shorts in G/F diets. The second objective was to investigate the effect of reducing the energy density of G/F diets (and therefore the feed efficiency of the animals), whilst offering co-product based diets on the environmental impacts of pig systems.

2. Materials and methods

Experiment 1 examined the effect of including different co-products in G/F diets on the environmental impacts of Canadian pig farming systems; the inclusion of each co-product was assessed individually. Experiment 2 tested the effect of lowering the energy density of the G/F diets incrementally when formulating for least cost; reflecting the fact that commercial diets are not always formulated to maximise feed efficiency (Saddoris-Clemons et al., 2011; Ferguson, 2014).

2.1. The diets

Experiment 1: The co-products investigated were: meat (pork) meal, bakery meal, corn DDGS and wheat shorts. The consequences of their inclusion in G/F diets were compared individually to a control diet. The control diet was a simplified typical G/F diet for East Canadian pig systems; it contained none of the co-products tested and was based on corn/soybean meal. The overall ingredient and nutrient composition (across all 4 feeding phases) of the diets in Experiment 1 are in Table 1; further details on the diet compositions for each feeding phase are in Appendix A1. All G/F diets had nutritional specifications designed for optimum feed efficiency, following expert industry advice, as well as complying with NRC nutrient requirements (NRC, 2012a). All G/F diets were formulated for a 4 phase feeding programme (starter, grower, finisher and late finisher) on a least cost basis, using Canadian price data for 2013 provided by Trouw Nutrition Canada (unpublished data, see Appendix B for the price ratios). The inclusion levels for each co-product were fixed to a maximum level in each feeding phase; for justification of the co-product inclusion levels see Section 2.2 below. The gestation, lactation and nursery diets were identical for all scenarios tested in this study, the composition of these diets can be found in Mackenzie et al. (2015).

Nutritional values for all ingredients in the diets were primarily taken from the Stein Monogastric Nutrition Laboratory ingredient matrix (Stein Monogastric Nutrition Laboratory, 2014). In cases where certain values were missing (or ingredients themselves were missing from the matrix), values from the NRC feed ingredient tables (NRC, 2012b) and the Premier Nutrition Atlas (Premier Nutrition, 2010) were used.

Experiment 2: The diets in Experiment 2 were designed to represent different feeding strategies pig producers may adopt to minimise feed cost per kg LW gain, as feed prices fluctuate. All diets were formulated on a least cost basis, with the inclusion of all co-products (with the exception of corn DDGS) permitted up to their maximum inclusion limits (Section 2.2). Experiment 1 showed that corn DDGS inclusion caused large increases in the environmental impacts of diets per kg of feed from some impact categories (see results), as such it was not included in experiment 2. The control diet was formulated using the same nutritional specifications as Experiment 1 and was designed for optimum feed efficiency (OP). Nutrient to net energy (NE) ratios remained greater than or equal to those of the OP diet for all subsequent diets. Further diets with specifications set at 97.5%, 95% and 92.5% the energy density of the OP diet were formulated, henceforth referred to as 0.975 OP, 0.95 OP and 0.925 OP. Energy was assumed to be the first limiting resource for growth in all diets. It was assumed that when the pigs were fed diets of reduced energy density, feed intake increased to achieve the same overall intake of NE across each feeding phase (Kyriazakis and Emmans, 1995). The overall ingredient and nutrient composition of the diets in Experiment 2 across all 4 feeding phases are in Table 2, with further details in Appendix A2.

2.2. Maximum inclusion levels

The maximum levels of inclusion used for each dietary phase for all the co-products investigated in this study are in Table 3. These were defined (on an as fed basis) to levels where each ingredient could be included in pig diets without negatively affecting pig performance. The levels were set based on existing literature specific to the co products in question, as well as advice on current practices in commercial formulation.

2.2.1. Meat meal

Meat meal refers to rendered animal material not including hair, hoof, horn, hide trimmings or manure as defined in article 5.1.6 of the Canadian 1983 Feeds Act (Government of Canada, 1983). In this case the animal material was assumed to be from rendered swine carcasses. Inclusions of between 5 and 7.5% meat meal in balanced G/F diets were not considered to affect feed conversion ratio (FCR) or average daily gain (ADG) performance in accordance with published guidelines (Bogges et al., 2008; Cromwell, 2006; OMAFRA, 2012a).

2.2.2. Bakery meal

Bakery meal is surplus material from industrial baking processes (such as bread or cakes); after further processing it is sold as an ingredient for animal feed. It is defined under article 4.6.1 of the Canadian Feeds Act (Government of Canada, 1983). Very few published studies, with the exceptions of Almeida et al. (2011) and

Table 1
The overall ingredient and nutritional composition (across all 4 feeding phases) of the grower/finisher diets tested in Experiment 1. The meat meal, bakery meal, corn DDGS and wheat shorts diets were the outcome of least cost formulations which included the maximum amount of these co-products. All ingredient inclusions shown in g/kg as fed; all nutrient levels shown as % as fed unless otherwise stated.

Ingredient	Control	Meat meal	Bakery meal	Corn DDGS	Wheat shorts
Canola Meal	168.6	151.8	171.1	61.2	68.2
Corn	727.8	702.9	645.8	567.4	487.3
Corn DDGS	0.00	0.00	0.00	260.6	0.00
Meat meal	0.00	64.6	0.00	0.00	0.00
Bakery Meal	0.00	0.00	86.60	0.00	0.00
Soymeal de-hulled	75.8	67.3	69.4	59.8	102.7
Wheat shorts	0.00	0.00	0.00	0.00	291.4
Limestone	12.2	3.44	12.04	14.2	14.2
Mono-calcium Phosphate	3.28	0.00	2.85	1.32	0.36
Lysine HCL	2.30	1.06	2.47	3.75	1.97
Liquid methionine	0.07	0.04	0.09	0.03	0.18
L Threonine	0.53	0.20	0.57	0.43	0.48
L Tryptophan	0.00	0.00	0.00	0.09	0.00
Canola Oil	0.00	0.00	0.00	0.00	24.3
Animal-vegetable fat blend	5.20	4.39	4.88	27.0	4.61
Additives	4.26	4.26	4.26	4.26	4.26
Resource					
Net Energy (MJ/kg)	9.81	9.81	9.81	9.81	9.81
Dig Crude Protein	13.26	14.69	13.22	13.84	13.50
Dig Arginine	0.85	0.98	0.84	0.78	0.96
Dig Histidine	0.41	0.43	0.40	0.41	0.43
Dig Ileum	0.51	0.56	0.51	0.53	0.53
Dig Leucine	1.21	1.31	1.19	1.50	1.15
Dig Lysine	0.80	0.80	0.80	0.80	0.80
Dig Methionine	0.26	0.29	0.26	0.28	0.26
Dig Phenylalanine	0.61	0.66	0.61	0.68	0.64
Dig Threonine	0.52	0.53	0.52	0.52	0.52
Dig Tryptophan	0.14	0.14	0.14	0.13	0.16
Dig Valine	0.62	0.70	0.62	0.66	0.66
Dig Cysteine	0.26	0.26	0.26	0.26	0.26
Dig Meth + Cys	0.53	0.55	0.53	0.53	0.51
Ca	0.69	0.69	0.69	0.69	0.69
P	0.50	0.63	0.50	0.48	0.56
Dig P	0.24	0.37	0.24	0.27	0.28
K	0.58	0.57	0.58	0.65	0.76
Crude Protein	16.48	18.66	16.55	17.52	17.66

Rojas et al. (2014) have comprehensively investigated its use as a feed ingredient in pig diets. The amino acid profile of bakery meal is comparable to corn, although high processing temperatures may reduce its lysine availability (Almeida et al., 2011). Bakery meal also contains high levels of salt. Concerns about variability and consistency prevent greater utilisation of bakery meal in commercial pig diets (Bogges et al., 2008; OMAFRA, 2012a). No peer reviewed studies could be found citing maximum inclusions for bakery meal in pig diets or specifically testing the effect of bakery meal on pig performance. Due to the highly variable nature of this ingredient, maximum inclusion levels were limited to 10% to ensure there would be no effect pig performance in diets of equivalent nutritional specification.

2.2.3. Corn DDGS

Corn DDGS is a co-product of the process by which ethanol is produced from corn (Shurson et al., 2012), and is defined under article 5.5.9 of the Canadian Feeds Act (Government of Canada, 1983). Recent reviews (Gutierrez et al., 2014; Stein and Shurson, 2009; Woyengo et al., 2014) suggest that corn DDGS can be included in pig G/F diets at levels up to 30% in grower and finisher diet phases without negative effects on pig performance in terms of ADG and FCR. These studies assume a crude fat content of ~10% for corn DDGS and a similar NE value to corn. The carcass yield of pigs fed corn DDGS at levels over 15% in G/F diets may be reduced by up to 1% (Graham et al., 2014; Woyengo et al., 2014) because of higher gut fill. This reduction in carcass yield was applied in this study.

2.2.4. Wheat shorts

As defined under article 4.2.17 of the Canadian feeds act (Government of Canada, 1983) wheat shorts are a co-product of wheat milling for flour in the North America. Wheat shorts contain fine bran particles, germ and a small portion of floury endosperm with crude fibre levels of <9%. Stein and Lange de (2007) cite maximum inclusion levels of 10% for wheat shorts in nursery diets and 40% in finisher and sow diets without any adverse effects on performance. Results published by Stewart et al. (2013) suggested that 30% inclusion of wheat shorts in starter diets (for pigs 25–55 kg LW) reduced ADG and increased FCR, although 30% inclusion during later dietary phases did not negatively affect these traits. Similar to corn DDGS large proportional inclusions of wheat shorts in G/F diets have been associated with reductions in carcass yield by up to 2% (Libao-Mercado et al., 2004); an average reduction of 1% was assumed in this study.

2.3. The LCA model

All environmental impact calculations in this study were conducted using an LCA model for pig systems in Canada; for a full description of the assumptions in this model refer to Mackenzie et al. (2015). The main details and in particular any deviations from the methods in that study are given below. The system boundaries of the LCA were cradle to farm-gate and the functional unit was 1 kg expected carcass weight (ECW). The environmental impacts of producing 1 kg of G/F feed were also calculated as part of

Table 2
The overall ingredient and nutritional composition (across all 4 feeding phases) of the grower/finisher diets tested in Experiment 2. The OP diet was a least cost formulation designed for Optimum Feed Efficiency. The subsequent diets shown were formulated at 97.5%, 95% and 92.5% the nutritional density of the OP diet (the 0.975 OP. 0.95 OP and 0.925 Op diets). All ingredient inclusions shown in g/kg as fed, all nutrient levels shown as % as fed unless otherwise stated.

Ingredient	OP	0.975 OP	0.95 OP	0.925 OP
Canola Meal	150.1	130.1	93.8	58.4
Corn	642.3	663.2	592.7	543.4
Corn DDGS	0.00	0.00	0.00	0.00
Meat meal	0.63	1.42	3.97	1.64
Bakery Meal	82.2	28.3	28.3	5.95
Soymeal de-hulled	69.4	64.6	64.4	70.3
Wheat shorts	25.9	89.4	191.2	287.2
Limestone	12.4	12.6	17.6	25.7
Mono-calcium Phosphate	2.59	1.85	0.42	0.00
Lysine HCL	2.72	2.70	2.60	2.45
Liquid methionine	0.12	0.11	0.13	0.16
L Threonine	0.71	0.69	0.66	0.61
L Tryptophan	0.00	0.00	0.00	0.00
Canola Oil	0.50	0.00	0.00	0.00
Animal-vegetable fat blend	6.15	0.82	0.00	0.00
Additives	4.26	4.26	4.26	4.26
Nutrient				
Net Energy (MJ/kg)	9.81	9.56	9.32	9.07
Dig Crude Protein	12.94	12.63	12.42	12.21
Dig Arginine	0.82	0.81	0.82	0.84
Dig Histidine	0.39	0.38	0.38	0.38
Dig Ileum	0.50	0.48	0.48	0.47
Dig Leucine	1.16	1.14	1.10	1.07
Dig Lysine	0.80	0.78	0.76	0.74
Dig Methionine	0.26	0.25	0.25	0.24
Dig Phenylalanine	0.60	0.58	0.58	0.58
Dig Threonine	0.52	0.50	0.49	0.48
Dig Tryptophan	0.14	0.13	0.14	0.14
Dig Valine	0.61	0.60	0.59	0.59
Dig Cysteine	0.26	0.25	0.24	0.24
Dig Meth + Cys	0.51	0.50	0.49	0.48
Ca	0.69	0.67	0.84	1.12
P	0.49	0.50	0.52	0.54
Dig P	0.24	0.24	0.25	0.27
K	0.58	0.60	0.65	0.70
Crude Protein	16.25	16.05	16.14	16.15

the analysis. There were three main compartments of material flow in the Life Cycle Inventory (LCI): 1) the production of feed ingredients, 2) the consumption of feed, energy and other materials for on-farm pig production and 3) the storage and land application of manure. The latter included replacing the need to use mineral fertiliser through using manure as an organic fertiliser. The LCA modelled three separate stages in the pig production system; 1) breeding (including suckling piglets), 2) nursery (up to ~28 kg) and 3) grower/finisher (from nursery end to finishing weight). The inputs to the model reflected typical practices for pig production in Eastern Canada (provinces of Ontario and Quebec) which represents around 56% of Canadian pig production (Brisson, 2014).

2.3.1. Feed production

The average environmental impacts per kg of ingredient for all ingredients used in the G/F diets can be found in Table 4. Where necessary economic allocation was used as the methodology for co-product allocation throughout the feed supply chain, as advised in the FAO LEAP recommendations (LEAP, 2014). The price ratios found in Appendix B were used for the purposes of economic allocation. The corn-soymeal based G/F diets tested in this study were typical of diets fed in Eastern Canadian pig systems and also reflective of diets more widely adopted in pig production in the USA. In Canada >90% of corn and 78% soybeans produced are grown in Ontario and Quebec, conversely >90% of canola, wheat and barley are produced in the western provinces (Statistics-Canada, 2014). LCI data for the production of major crops was adapted from a previous LCA on Canadian crop production (Pelletier et al., 2008). The LCI data for amino acids lysine, methionine, threonine and tryptophan was taken from Garcia-Launay et al. (2014). LCI data for the production of minerals mono-calcium phosphate, salt and limestone came from the Ecoinvent databases (Swiss Centre for Life Cycle Inventories, 2007). Corn DDGS was assumed to be sourced from Canadian bioethanol producers. LCI data for corn DDGS was adapted from data representative of ethanol production in the USA (Swiss Centre for Life Cycle Inventories, 2007) to reflect Canadian inputs of corn and energy. The LCI for bakery meal was based on data provided by a large retailer of bakery meal (Sugarich, personal communication) and adapted for a Canadian scenario. Surplus material from bread production is a large proportion of the material used for bakery meal that is sold for use in monogastric diets (Sugarich, personal communication). Bread was used as a representative input material to bakery meal in this study. The LCI for the production of 1 kg bread was adapted from the LCA food database (Nielsen et al., 2003) with the input of Canadian wheat and energy sources. A price ratio of 10:1 was assumed for bread and surplus material, with on average 8% of material collected as surplus from the bread supply chain; either during the production process or discarded at the supermarket (Sugarich, personal communication). Processing inputs for packaging removal, drying and grinding were estimated to be 20 kWh electricity and 62 kWh natural gas per tonne of material processed (Sugarich, personal communication). LCI data for meat meal was adapted from a previous LCA study on rendering, the yields by mass from rendering 57.7% for fat and 42.3% for meat meal on average (Ramirez et al., 2012). The price ratio of rendered fat: meat meal was assumed to be 1.22 (unpublished data provided by Trouw Nutrition Canada. see Appendix B). The LCI data for wheat milling was adapted from Ecoinvent (Ecoinvent centre, 2007) in order to represent Canadian energy inputs. Bread flour yield was estimated to be 73% on average, with remaining material flows of 2% wheat germ, 12.5% wheat shorts and 12% wheat bran (Blasi et al., 1998). A price ratio of 1:0.11:0.22:0.44 was assumed for wheat flour: wheat germ: wheat shorts: wheat bran (unpublished data provided by Trouw Nutrition Canada see Appendix B).

Table 3
Maximum inclusion limits (g/kg as fed) used in each feeding phase in the grower finisher diets for the co-products investigated in this study.

Stage	Meat meal	Bakery meal	Corn DDGS	Wheat shorts
Starter	50	50	200	200
Grower	50	75	300	300
Finisher	75	100	300	400
Late Finisher	75	100	200	200

2.3.2. Farm model

The baseline herd performance characteristics (FCR, litter size, mortality etc.) used in this study were the same as those modelled for pig systems in Eastern Canada in Mackenzie et al. (2015). The data collected represented the performance of 73,000 sows from 85 herds, 1.5 million nursery pigs (approx. 430 herds) and >1 million finished pigs (approx. 470 herds). The retention of N in the finished pigs was calculated using the principles of Wellock et al. (2004) and was assumed to be 0.0256 BW ± 0.00128. Retention of P and K were calculated using an isometric relationship of body composition to BW (Lenis & Jongbloed, 1994; Symeou et al., 2014) and were assumed to be approx. 0.005 BW ± 0.00025 and 0.002 BW ± 0.0001 respectively. For K this assumption represents a linear approximation around slaughter weight of a curvilinear

Table 4
Average environmental impacts per kg for all feed ingredients included in grower/finisher diets in the scenarios tested.

Impact category[a]	NRE	NRRU	AP	EP	GWP
Unit[b]	MJ	kg Sb eq	kg SO_2 eq	kg PO_4 eq	kg CO_2 eq
Canola meal	3.2	1.39E-03	7.97E-03	1.59E-03	0.30
Canola oil	8.9	3.84E-03	2.20E-02	4.40E-03	0.84
Corn	4.0	1.71E-03	5.13E-03	1.11E-03	0.39
Soya meal	1.3	5.70E-04	4.11E-03	8.71E-04	0.15
Wheat	4.2	1.84E-03	1.01E-02	2.04E-03	0.43
Meat (pork) meal	2.4	1.05E-03	2.46E-04	6.16E-05	0.13
Corn DDGS	13.9	6.51E-03	1.13E-03	2.66E-04	0.78
Wheat shorts	1.2	5.12E-04	2.78E-03	5.59E-04	0.12
Bakery meal	1.2	5.17E-04	1.41E-03	2.60E-04	0.08
Animal-vegetable fat blend	5.9	2.57E-03	1.01E-02	2.06E-03	0.49
HCL-Lysine	83.0	3.51E-02	2.12E-02	9.97E-03	4.81
L-Threonine	83.0	3.51E-02	2.12E-02	9.97E-03	4.81
FU-Methionine	80.5	3.64E-02	7.54E-03	1.70E-03	2.95
L-Tryptophan	166.0	7.01E-02	4.24E-02	1.99E-02	9.62
Sodium Chloride	3.1	1.21E-03	8.97E-04	6.68E-04	0.18
Mono-calcium Phosphate	21.5	9.40E-03	2.68E-02	3.63E-04	1.51
Limestone	0.4	1.31E-04	1.03E-04	3.58E-05	0.02

[a] NRE = Nonrenewable energy use, NRRU = Nonrenewable resource use, AP = Acidification Potential EP = Eutrophication Potential, GWP = Global Warming Potential.
[b] eq = equivalent.

relationship (Rigolot et al., 2010). All N, P and K not retained by the finished pigs were assumed to be excreted in faeces or urine. Average expected carcass yield at farm gate was 80% (Mackenzie et al., 2015; Vergé et al., 2009). For the wheat shorts and corn DDGS diets in Experiment 1, and the 0.95 OP and 0.925 OP diets in Experiment 2 this was reduced by 1%. The adjustment was made to account for increased gut fill due to the high proportion of bulky feed ingredients included in these diets (Graham et al., 2014; Libao-Mercado et al., 2004; Woyengo et al., 2014). The on-farm energy consumption data was adapted from a detailed study of energy consumption in conventional pig housing systems in Iowa (Lammers et al., 2010). To reflect longer and colder Canadian winters in comparison to Mason City, Iowa (which was used in the Lammers et al. (2010) calculations), larger loads of Liquid Petroleum Gas (LPG) for heating were assumed to be required to maintain adequate barn temperatures. Temperature data for Mason City (U.S. Climate Data, 2014), and regional data for Eastern Canada (Weatherbase, 2014) showed average annual temperatures were around 28% lower in Eastern Canada. The LPG inputs for heating barns in Eastern Canada were estimated to be 25% higher than in the Iowa case study. While this was a rough estimate, a previous sensitivity analysis showed that it was not a sensitive assumption for any of the impact categories tested here (Mackenzie et al., 2015).

2.3.3. Manure model

The manure model estimated the emissions of CH_4, NH_3, N_2O, N_2 and NOx which occurred during housing, storage and application as well as the leaching of NO_3 and PO_4. Indirect N_2O formation resulting from NH_3 and NOx emissions and NO_3 leaching were also modelled in accordance with the IPCC (2006) principles. Manure was assumed to remain in the barn for up to 7 days; it was then transferred to outside storage (except in cases where storage was a pit beneath the barn). It was assumed to be applied to land twice annually in spring and autumn. The model of NH_3 emissions for housing and storage was based on a previous model of NH_3 emissions from pig production in Canada (Sheppard et al., 2010). A tier 2 IPCC methodology was adopted for emissions of CH_4, N_2O, NOx and NO_3, but adapted to reflect small N losses at housing. As average ambient temperatures were considered to be <0 °C during winter (Weatherbase, 2014), emissions during this period were considered negligible for outside storage methods. The proportional mix of floor types in pig housing, storage and application techniques was based on information from the Livestock Farm Practice Survey (Sheppard et al., 2010), as well as Statistics Canada records regarding the storage and application of swine manure (Beaulieu, 2004; Statistics-Canada, 2003). All N, P, K excreted in faeces or urine was assumed to be applied to land as fertiliser, once losses during housing and storage were accounted for. The manure as applied to land was assumed to replace the need to apply equivalent synthetic fertilisers at a rate of 0.75, 0.97 and 1 for N, P and K respectively (Nguyen et al., 2011). The proportional mixture of the types of synthetic fertilisers replaced by the NPK content of the manure in each region was derived from sales figures for Eastern Canada to assume a regional average fertiliser mix (Korol, 2004). Further details on the emission factors used, as well as the proportional mix of floor types in pig housing, manure storage types and application techniques assumed are given in Appendix C.

2.4. Environmental impact calculations

The impact categories quantified for this study were: Global Warming Potential (GWP), Eutrophication Potential (EP), Acidification Potential (AP), Nonrenewable Energy Use (NRE) and Nonrenewable Resource Use (NRRU). GWP was quantified as CO_2 equivalent: with a 100 year timescale; 1 kg CH_4 and N_2O emitted are equivalent to 25 and 298 kg CO_2 respectively (IPCC, 2006). EP, AP and NRRU were calculated using the method of the Institute of Environmental Sciences (CML) at Leiden University (http://www.leidenuniv.nl/interfac/cml/ssp/index.html). NRE was calculated in accordance with the IMPACT 2002+ method (Jolliet et al., 2003). The methodology used to account for the greenhouse gas emissions arising from land use changes followed PAS 2050 guidelines (BSI, 2011). All crops in the LCI of the feed supply chain in this study were assumed to be grown on arable land within North America that had been used for this purpose for ≥20 years, thus had no land use change-related greenhouse gas emissions associated with them. All environmental impact calculations for this study were conducted in the software package SimaPro 7.2.

2.5. Uncertainty analysis

The uncertainty analysis methodology used in this study is detailed in Mackenzie et al. (2015) Uncertainties were categorised as either specific to the system (α) or shared between the systems being compared (β). In Experiment 1, the co-product diets were each compared to the control diet using parallel Monte-Carlo simulations. In Experiment 2 the low energy density diets were individually compared to the OP diet in the same manner. Variation in all parameters except the G/F diet composition, feed intake during the G/F phase, nutrient excretion in the G/F phase and carcass yield were considered shared uncertainty in the comparisons. In Experiment 1 all diets met specifications designed for optimum feed efficiency, thus variation in feed intake was considered as β uncertainty. In Experiment 2 feed intake was assumed to increase as the energy density of the diets decreased, to achieve the same NE intake across each feeding phase (Kyriazakis and Emmans, 1995). However, all other variability in feed efficiency over the G/F phase was assumed to be intrinsic to the animal and its environment. This was modelled as shared uncertainty independent of the diet. Further details on the mean values and uncertainty ranges adopted for specific parameters within the model are provided in Appendix D.

3. Results and discussion

3.1. Experiment 1

The consequences of the individual co-product inclusions in G/F diets on the average environmental impacts for the production of 1 kg of feed are in Table 5. The environmental impact results of the diets tested in experiment 1 modelled per kg ECW from cradle to farm-gate are in Table 6.

3.1.1. Meat meal

The G/F diet including meat meal had lower average values for all environmental impact categories tested in this study than the control diet per kg of feed (Table 5). The inclusion of meat meal reduced NRRU and NRE per kg ECW by 9% and 8% respectively in comparison to the control ($P < 0.001$). However, EP and AP increased by 10% and 7% on average ($P < 0.001$), with no significant change in GWP (Table 6). As can be seen in Table 1 the meat meal G/F diet contained higher levels of N (by 10%) and P (by 26%) than the control G/F diet. This was because meat meal contained higher levels of crude protein than the two main protein sources in the control diet; soya meal and canola meal (Stein Monogastric Nutrition Laboratory, 2014). Lower digestible levels of certain amino acids (e.g. Tryptophan) in meat meal ensured it was not able to replace soya meal or canola meal at a rate >1 when added to the G/F diet. Therefore excretion of N and P was greater when meat meal was included in the G/F diet compared to the control, which caused the increases observed in AP and EP. Due to increased levels of nutrient excretion, no overall reduction in GWP per kg ECW was observed when comparing the meat meal diet to the control (Table 6). This was despite an average reduction of 5% in GWP per kg of feed (Table 5).

3.1.2. Bakery meal

The G/F diet including bakery meal had lower average impacts per kg of feed for every impact category tested than the control (Table 5). As well as this, the inclusion of bakery meal caused almost no change in the average N and P excretion in the system in comparison to the control. As a result the inclusion of bakery meal in the G/F diet produced small (<5% average) reductions for all impact categories tested ($P < 0.001$) per kg ECW compared to the control (Table 6). Unlike for wheat shorts and corn DDGS, there is a lack of peer reviewed work which has investigated the limits of including bakery meal in G/F diets without compromising pig performance. For this reason the levels of inclusion modelled in this study were conservative in comparison to guidelines on their potential inclusion limits in later stage pig diets (Bogges et al., 2008; OMAFRA, 2012a; Stein and Lange de, 2007). As such the results presented here may underestimate the potential of bakery meal inclusion to reduce the environmental impacts of pig systems.

3.1.3. Corn DDGS

The inclusion of corn DDGS in G/F diets increased average levels of NRRU (by 71%), NRE (by 68%) and GWP (by 30%) per kg of feed compared to the control diet (Table 5). The increase in NRRU, NRE and GWP per kg of feed was due to the high levels of impact per kg of DDGS (see Table 4). The GWP levels for corn DDGS per kg of ingredient in this study were similar to values reported for US production systems using equivalent allocation methods (Kraatz et al., 2013; Thoma et al., 2011). The corn DDGS diet had lower average EP (by 22%) and AP (by 20%) per kg of feed (Table 5). The inclusion of Corn DDGS in the G/F diets resulted in relatively large average increases in NRRU (56%) and NRE (48%) per kg ECW as well as a 16% increase in GWP ($P < 0.001$). The corn DDGS diet caused a small reduction in AP ($P = 0.01$) of <1% on average and did not significantly alter EP. Levels of N excretion were higher for the DDGS diet compared to the control due to increased dietary N content, although P excretion was slightly reduced (Table 1). As a result only a very small reduction was observed in AP for the DDGS diet, with no change in levels of EP per kg ECW. The inclusion of corn DDGS in pig diets increased GWP per kg ECW and this was in agreement with previous results published by Thoma et al. (2011).

3.1.4. Wheat shorts

When calculated per kg of ingredient wheat shorts had the lowest levels of NRRU, NRE and the second lowest GWP of the co-products investigated in this study (Table 4). Wheat shorts also had the highest overall inclusion levels of any of the feed co-products in G/F diets (Table 1). Average levels of AP and EP per kg of feed were also lower for the wheat shorts diet by 12% and 13% respectively when compared to the control diet (Table 5). The consequence of this was that of the co-products tested, the maximum inclusion of wheat shorts produced the largest reductions in NRRU (19%), NRE (19%) and GWP (12%) respectively per kg ECW ($P < 0.001$). The inclusion of wheat shorts at these levels in G/F diets did not significantly affect the AP or EP of the system (Table 6). Increased N and P excretion caused by the wheat shorts diet meant AP and EP from the manure management system actually increased, offsetting the decrease in AP and EP per kg of diet. This meant there was no significant difference in the result per kg ECW for these impact measures.

Table 5
The average levels of environmental impact **per kg of feed** for grower/finisher diets tested Canadian pig production. The meat meal, bakery meal, corn DDGS and wheat shorts diets were least cost formulations which included the maximum amount of these co-products.

Impact category[a]	Control	Meat meal	Bakery meal	Corn DDGS	Wheat shorts
Nonrenewable resource use (g Sb eq)	1.90	1.81	1.82	3.25	1.57
Acidification potential (g SO_2 eq)	5.71	5.30	5.32	4.46	5.03
Eutrophication potential (g PO_4 eq)	1.22	1.14	1.16	0.98	1.08
Global Warming Potential $_{100}$ (kg CO_2 eq)	0.40	0.38	0.38	0.52	0.33
Nonrenewable energy use (MJ)	4.49	4.27	4.27	7.32	3.70

[a] eq = equivalent.

Table 6
The environmental impacts of **1 kg expected carcass weight** at farm gate for grower/finisher control and co-product diets tested in an LCA of Canadian pig production. The meat meal, bakery meal, corn DDGS and wheat shorts diets were least cost formulations which included the maximum amount of these co-products. The control diet was a simple corn based diet containing none of these ingredients.

Impact category[a]		Control	Meat meal	Bakery meal	Corn DDGS	Wheat shorts
Nonrenewable resource use (g Sb eq)	Mean	6.52	5.95	6.36	10.2	5.28
	s.d.	0.90	0.81	0.96	1.8	1.16
	% < control[b]	N/A	100	100	0	100
Acidification potential (g SO_2 eq)	Mean	57.4	61.6	55.8	56.5	56.9
	s.d.	4.2	5.0	4.8	4.0	4.2
	% < control[b]	N/A	0	100	99	70.8
Eutrophication potential (g PO_4 eq)	Mean	14.4	15.8	14.1	14.3	14.6
	s.d.	1.8	2.0	1.7	1.8	1.8
	% < control[b]	N/A	0	100	56.4	15.6
Global Warming Potential $_{100}$ (kg CO_2 eq)	Mean	2.20	2.16	2.13	2.55	1.95
	s.d.	0.19	0.20	0.18	0.21	0.18
	% < control[b]	N/A	80.8	100	0	100
Nonrenewable energy use (MJ)	Mean	15.8	14.6	15.4	23.5	12.9
	s.d.	1.9	1.7	2.0	3.7	2.0
	% < control[b]	N/A	100	100	0	100

[a] eq = equivalent.
[b] The percentage of results (from 1000 simulations) where the impacts for the treatment diet were lower than the control diet.

3.2. Experiment 2

Table 7 shows the environmental impacts for 1 kg ECW from cradle to farm gate for the diets tested in Experiment 2, when the energy density of the G/F diets was reduced on a sliding scale. Each incremental reduction of energy density in the diets tested in Experiment 2 increased the combined inclusion of co-products (wheat shorts, bakery meal and meat meal), although this increase was not linear. The OP diet contained 108 g/kg co-products, the 0.975 OP diet 119 g/kg, the 0.95 OP diet 223 g/kg and the 0.925 OP diet 294 g/kg combined co-products. As such the linear reduction of energy density in G/F diets did not have a linear effect on the environmental impacts of the system.

When compared to the OP diet the 0.975 OP diet increased AP ($P < 0.001$), EP ($P < 0.001$), GWP ($P < 0.001$) and NRE ($P = 0.018$) with average increases of <1% in all cases. NRRU was not significantly different between the OP and 0.975 OP diets.

The 0.95 OP diet caused average reductions of 4% and 6% for NRE and NRRU respectively relative to the OP diet ($P < 0.001$). AP and EP for the 0.95 OP diet increased by 1% and 3% on average in comparison to the OP diet ($P < 0.001$). There was no significant difference in GWP between the 0.95 OP and OP diets.

Compared to the OP diet, the 0.925 OP diet reduced average levels of both NRE and NRRU by 9% ($P < 0.001$) and reduced GWP by 4% ($P = 0.018$) per kg ECW. The 0.925 OP diet caused marginal average increases of <1% and 1% for AP an EP respectively ($P < 0.001$) compared to the OP diet.

All G/F diets of reduced energy density tested in Experiment 2 increased levels of EP and AP when compared to the OP diet. As all diets had similar contents of crude protein and P to the OP diet (Table 2), this combined with incremental reductions in feed efficiency resulted in a linear increase in the levels of N and P excretion. However, the observed increase in these two impact categories was not linear as feed efficiency declined, with average AP and EP levels lower for the 0.925 OP diet than the 0.95 OP diet. In Experiment 1 increased inclusions of meat meal, bakery meal and wheat shorts in G/F diets all reduced the AP and EP per kg of feed, with wheat shorts causing the largest reduction (Table 6). The high levels of co-product inclusion in the 0.95 OP and 0.925 OP diets largely offset the increases in N and P excretion, meaning only relatively small increases in EP and AP were observed compared to the OP diet. The reduced GWP per kg feed in the 0.925 OP diet (due to the high levels of wheat shorts) compared to the OP diet, resulted in an overall reduction in GWP per kg ECW. This was despite the reduction in feed efficiency and increased N and P excretion.

Table 7
The environmental impact of 1 kg **expected carcass weight** at farm gate for grower/finisher diets Canadian pig production. The OP diet was a least cost formulation designed for optimum feed efficiency. The other three diets shown were formulated at 97.5%, 95% and 92.5% the energy density of the OP diet (the 0.975 OP. 0.95 OP and 0.925 OP diets).This allow for a higher inclusion of co-products in these diets.

Impact category[a]		OP	0.975 OP	0.95 OP	0.925 OP
Nonrenewable resource use (g Sb eq)	Mean	6.42	6.38	6.02	5.85
	s.d.	0.91	0.88	0.81	0.91
	% < OP[b]	N/A	12.4	100	100
Acidification potential (g SO_2 eq)	Mean	56.1	56.5	56.8	56.2
	s.d.	4.3	4.1	4.3	4.4
	% < OP[b]	N/A	0	0	0
Eutrophication potential (g PO_4 eq)	Mean	14.2	14.3	14.6	14.4
	s.d.	1.7	1.8	1.8	1.8
	% < OP[b]	N/A	0	0	0
Global Warming Potential $_{100}$ (kg CO_2 eq)	Mean	2.16	2.16	2.13	2.08
	s.d.	0.19	0.20	0.19	0.19
	% < OP[b]	N/A	0	86.6	98.2
Nonrenewable energy use (MJ)	Mean	15.5	15.5	14.6	14.2
	s.d.	1.9	1.9	1.7	1.9
	% < OP[b]	N/A	1.8	100	100

[a] eq = equivalent.
[b] The percentage of results (from 1000 simulations) where the impacts for the treatment diet were lower than the OP diet.

The results in Table 7 show that formulating for optimum feed efficiency only minimised the environmental impact of the pig farming system for 2 of the 5 impact categories considered. The increased inclusion of co-products with low environmental impacts in the least energy dense diet resulted in reductions in GWP, NRE and NRRU per kg ECW; even when reduced feed efficiency and the effect of increased N and P excretion on the manure management system were accounted for.

3.3. General discussion

Concerns over food security mean there is increased pressure on commercial animal production systems to use less human edible feedstuffs in animal feed (Steinfeld et al., 2006). Co-products from the human food supply chain and biofuel industry, not suitable for human consumption, represent a means of reducing the amount of human edible food contained in animal feed. The use of such co-products in commercial pig diets has increased in recent years due to a sustained period of price increases and price volatility for traditional cereal grains and protein meals (Woyengo et al., 2014). While the benefits of using co-products in pig diets in improving sustainability of the system are clear from an economic and social perspective, the implications for the environmental impact of the system are less so. As such, Experiment 1 represented an important step to quantify the environmental implications for including specific co-products in G/F diets using a representative LCA model of Canadian pig production. Previous LCA studies that investigated the effect of altering the ingredient composition of G/F diets on the environmental impacts of pig farming systems have mainly focussed on two areas: 1) the impact of crystalline amino acid supplementation (Garcia-Launay et al., 2014; Mosnier et al., 2011; Ogino et al., 2013) and 2) the use of alternative protein sources to replace soya meal in European systems (Eriksson et al., 2005; Meul et al., 2012). Meul et al. (2012) also investigated the effect of maximising co-product inclusion on the carbon footprint of European pig diets (per kg feed), but did not investigate the co-products included in this study. The implications for the environmental impacts of pig systems when specifically including meat meal, bakery meal or wheat shorts in G/F diets have not previously been presented in an LCA to our knowledge.

The results from Experiment 1 highlight the importance of including nutrient excretion and manure management in any assessment of the environmental impact of feed choice in livestock systems. If Experiment 1 only considered the environmental impacts of the feed production chain, its conclusion would have been that increased inclusions of meat meal, bakery meal and wheat shorts individually in iso-energetic diets reduced all environmental impact categories tested (Table 5). As can be seen in Table 6 however, this was not the case when accounting for the impacts from manure management; meat meal inclusion increased AP and EP levels and wheat shorts inclusion caused no significant reduction in AP or EP. Accounting for the environmental impacts of feed production from cradle to feed mill gate is therefore not sufficient when assessing feed choices in livestock systems, even when comparing diets which are assumed to cause no differences in feed intake.

The results of LCA studies of livestock systems are sensitive to the methodological approach adopted for co-product allocation (e.g. Cederberg and Stadig, 2003; Nguyen et al., 2011). A hierarchy for allocation methodologies is set out in ISO 14044; this states that when allocation cannot be avoided, it should preferably be based on physical relationships between the inputs and outputs (ISO, 2006). However, in many studies of agricultural systems (including the present one), allocation between co-products is based on the economic value of co-products, not on any functional relationships within the system (Ardente and Cellura, 2012). The main reason for this is that it is not possible in many cases, to identify causal physical relationships in the biological processes behind the agricultural production. Amongst the potential non-functional shared properties such as mass, gross energy, etc., the economic value of co-products can be seen as the most direct measure of their importance in production decisions. However there are drawbacks to adopting this methodology such as the inherent variability of commodity prices (Ardente and Cellura, 2012).

Concerns regarding variability in nutritional content continue to inhibit the use of co-products in commercial pig diets (Zijlstra and Beltranena, 2013). As well as variability alternative ingredients often have a high content of at least one anti-nutritional factor, which further inhibits their potential inclusion in pig diets (Woyengo et al., 2014). There remains a knowledge gap regarding how to account for the effect of the increased levels of nutritional variability caused by high levels of co-products on animal performance. Greater understanding of the implications of this variability for animal performance would enable a more complete assessment of the environmental impacts of feed choices involving variable co-products. Without the tools to confidently predict the effect of increased nutritional variability in diets on animal performance, nutritionists will often be cautious in their recommendations for including co-products in animal diets. The risks of such variability can be partially mitigated through the regular testing of ingredients as they are brought to the mill. Near Infrared Spectroscopy can be used to this effect as long as calibration using wet chemistry has been undertaken (OMAFRA, 2012b).

Diets in commercial pig production systems are formulated for economic outcomes in most cases. When formulating for such outcomes, diets are best optimised using linear programming for a specific goal using a growth model, without formulating for a fixed nutritional specification (Ferguson, 2014). This means diets are not always formulated for optimum levels of feed efficiency (as in Experiment 1), as there is a trade-off between feed cost and feed efficiency. If nutrient to NE ratios are fixed in the diet formulation rules, then as feed prices fluctuate so will the energy density of the optimum solution for a particular economic objective. At lower ingredient prices the solution will tend towards a lower energy diet with increased inclusion of low value co-products, such as wheat shorts (Saddoris-Clemons et al., 2011). This phenomenon was represented here by formulating least cost G/F diets at 4 incremental levels of energy density. To our knowledge, no LCA of pig farming systems has investigated the consequences of reducing the energy density of G/F diets on the environmental impact of the pig farming system when formulating for least cost. Just as there is a trade-off between feed intake and feed cost in diet formulation, there is a trade-off between feed intake and resulting nutrient excretion with the environmental impact per kg of a diet in pig systems for any given impact category. Experiment 2 showed this trade-off differed between impact categories; for NRRU, NRE and GWP the least energy dense diet tested had the lowest levels of these impact categories, conversely the most energy dense diet caused the lowest levels of EP and AP.

The results of Experiment 2 also demonstrate that when accounting for multiple environmental impact categories in livestock systems, feed choices can present trade-offs between different categories of environmental impact. Eriksson et al. (2005) also observed a trade-off between reducing GWP but increasing EP and AP when modelling a scenario for replacing soya meal with peas in European pig systems. The environmental impact trade-offs associated with feed choice have not been explored extensively in the case of pig systems, due to the limited number of studies in this area. Pork production has been shown to have relatively low levels of GWP in comparison to meat production from ruminants (De Vries and de Boer, 2010; Eshel et al., 2014; Williams et al., 2006). However when using other environmental impact measures such as EP, AP and NRRU the impacts of pork production have been shown to be similar to those from beef production (De Vries and de Boer, 2010; Williams et al., 2006). This is an important consideration when looking at the potential of co-products to reduce the environmental impacts of pig farming systems. For instance if AP and EP are seen as the most important environmental impacts of pig farming systems, the reductions in other impact categories shown by diets with higher levels of co-products in Experiment 2, may not be seen as beneficial enough to outweigh increases in AP and EP. This study focused specifically on testing scenarios to ask whether co-products can be used as feed to reduce the environmental impact of pig systems. With further integration of a LCA model to a diet formulation tool, it would be possible to formulate diets to minimise specific types of environmental impact in a more holistic manner.

4. Conclusions

The environmental implications for pig farming systems of relatively high inclusion levels of co-products in G/F diets formulated for economic goals were quantified. Increased inclusions of co-products; such as bakery meal and wheat shorts in G/F diets formulated for economic goals can reduce the GWP, NRE and NRRU of Canadian pig farming systems. The least energy dense diet, with the greatest inclusions of co-products reduced GWP, NRE and NRRU, but caused small increases to AP and EP (<1%) per kg ECW when compared to a least cost diet formulated for optimum feed efficiency. These results suggest an overall benefit to increasing the use of co-products in G/F diets for the environmental impact of pig farming systems. The implications of utilising meat meal, bakery meal and wheat shorts individually in G/F diets for the environmental impact of pig systems were also modelled for the first time. The inclusion of bakery meal in G/F diets of equivalent nutritional specification reduced the environmental impacts of the system for every impact category modelled. Maximum inclusion of wheat shorts in diets formulated for the same specification was shown to cause reductions in GWP NRE and NRRU of >10% with no significant effect on AP and EP. This study showed that an increased inclusion of co-products in G/F diets can reduce the environmental impact of pig farming system in some cases. These findings add to a broader aim of identifying nutritional strategies to reduce the environmental impact of pig farming systems.

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Appendix A. Supplementary data

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