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Environmental impact of using specialty feed ingredients in swine and poultry production: A life cycle assessment[1]

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ABSTRACT: Livestock production has a variety of environmental impacts such as greenhouse gas emissions, water pollution, acidification, and primary energy consumption. The demand for livestock products is expected to grow substantially, creating even more environmental pressure. The use of specialty feed ingredients (SFI) such as supplemented AA and phytase can reduce nutrient input into the system without compromising productivity and consequently can reduce emissions. The global change impact of using SFI in pig and broiler production systems in Europe and North and South America was studied. A life cycle assessment according to international standards (ISO 14040/44) analyzed contributions from producing SFI and animals to global change. Three different alternatives were analyzed. In addition, partial sensitivity analysis was conducted using 5 scenarios for each region for both production systems. Specialty feed ingredient supplementation in pig and broiler diets reduced greenhouse gas emissions (cradle to farm gate) by 56% and 54% in Europe, 17% and 15% in North America, and 33% and 19% in South America, respectively, compared to an unsupplemented diet. A total of 136 Mt CO_2 equivalent (CO_2 eq) was saved in 2012, rising to 146 Mt CO_2 eq in 2050 on the basis of United Nations population projections. Considerable benefits of supplementation with SFI were apparent in European and South American diets when direct land use change was considered because of the reduced demand for soybean meal. The eutrophication potential of unsupplemented diets was reduced by up to 35% in pig and 49% in broiler production systems compared to supplemented alternatives. The acidification potential of supplemented strategies was reduced by up to 30% in pig and 79% in broiler production systems. The primary energy demand was similar in all alternatives, and this could be an area where the SFI industry can improve. Overall, SFI supplementation substantially reduced the global warming, eutrophication, and acidification potentials in all regions studied.

Key words: broiler, direct land use change, life cycle assessment, livestock emissions, pigs, specialty feed ingredients

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INTRODUCTION

The global population is projected to reach more than 9 billion people in the next 4 decades (Food and Agriculture Organization [**FAO**], 2014) with a concomitant 60% increase in demand for food (Alexandratos and Bruinsma, 2012). As a consequence of this rising demand, livestock production is expected to double by 2050 (Garnett, 2009). Several studies indicated that the livestock sector significantly contributes to global environmental change (e.g., De Vries and De Boer, 2010). In pig and poultry production, the impact on the environment is mainly from 1) excretion of excess nitrogen and phosphorus, leading to the deterioration of aquatic systems (Conley et al., 2009), 2) direct greenhouse gas (**GHG**) emissions from manure storage and application to the field, which contributes to climate change (Tubiello et al., 2013), and 3) ammonia emissions responsible for acidification and eutrophication of N-limited ecosystems (Sutton et al., 2008).

Formulating diets with only regular feedstuffs to meet requirements results in large excess of AA (NRC, 2012). Similarly, a considerable amount of P in pig and poultry diets is unavailable to the animal (Kebreab et al., 2012). Reducing intake of protein and P is the most effective way to reduce environmental impacts; however, this has to be achieved without impairing animal performance or negative environmental impact. Utilization of supplemental AA to meet protein requirements can reduce N excretion by 8% for every 1% unit reduction in dietary protein intake (Kerr 2003; NRC, 2012). The supplementation of animal feed with the enzyme phytase improves the availability and digestibility of organically bound plant P, leading to reduced use of inorganic P in feed formulation and subsequent decrease in P excretion (Kebreab et al., 2012). The production of specialty feed ingredients (**SFI**) such as supplemental AA and phytase also has an environmental footprint. To date, there has not been a comprehensive study that assessed the impact of multiple uses of SFI on the environmental impact of all stages in pig and poultry production. Therefore, our objective was to conduct a cradle–to–farm gate environmental performance of pig and broiler production with and without SFI supplementation using a life cycle assessment (**LCA**).

MATERIALS AND METHODS

The LCA was conducted using GaBi software version 6 (PE INTERNATIONAL AG, 2012) and conforms to ISO 14040/44 standards (Finkbeiner et al., 2006; International Organization for Standardization, 2006a,b; Finkbeiner, 2014a). The software includes GaBi content databases providing the costs, energy, and environmental impacts of sourcing and refining every raw material or processed component of a manufactured item. Where information for a product was missing, literature values were sourced and integrated in the GaBi software. The life cycle inventory for feed ingredients was taken from the food and feed extension database of GaBi software (http://www.gabi-software.com/deutsch/databases/gabi-databases/food-feed/) and implemented as reported by Liedke et al. (2014).

System Description

The livestock husbandry systems analyzed in the present study represent typical large-scale production systems in 3 regions of the world because of regional differences in pig and poultry production, i.e., Europe, North America, and South America. A simplified overview of the system boundary considered is shown in Fig. 1. Each production system was divided into 5 processes: production of base feed ingredients, production of SFI, preparation of feed, animal husbandry, and manure management (Fig. 1). The analysis considers all "upstream" activities from the extraction of raw materials to manufacturing of basic intermediate products, including transportation. For example, for fossil diesel use, extraction of crude oil, refinery, and transportation to the farm as well as the consumption in the truck or tractor on the farm were considered. The study boundary included all processes up to the animal farm gate (live weight, **LW**). Transportation between the subsystems was included. Further "downstream" activities such as processing, distribution, or consumption of animals were not taken into account, as they were considered to remain unchanged following the use of SFI. Manure management, which includes manure storage and field application, was considered. The quality of animal product and, consequently, further downstream processing steps were assumed not to be affected by the different feed compositions. The functional unit was 1 t of animal LW. The reference year was 2012, and production referred to this year was used as a reference time.

Alternatives

Three alternatives for each region in the study were analyzed. The alternatives were 1) standard base diet without any SFI supplementation (**A1**), 2) standard base diet supplemented with only AA (**A2**), and 3) standard base diet supplemented with AA and phytase (**A3**). The diets were representative of commercial production systems and formulated according to industry standard in each region. Both production systems are influenced by the level of feed conversion ratio (**FCR**), which is

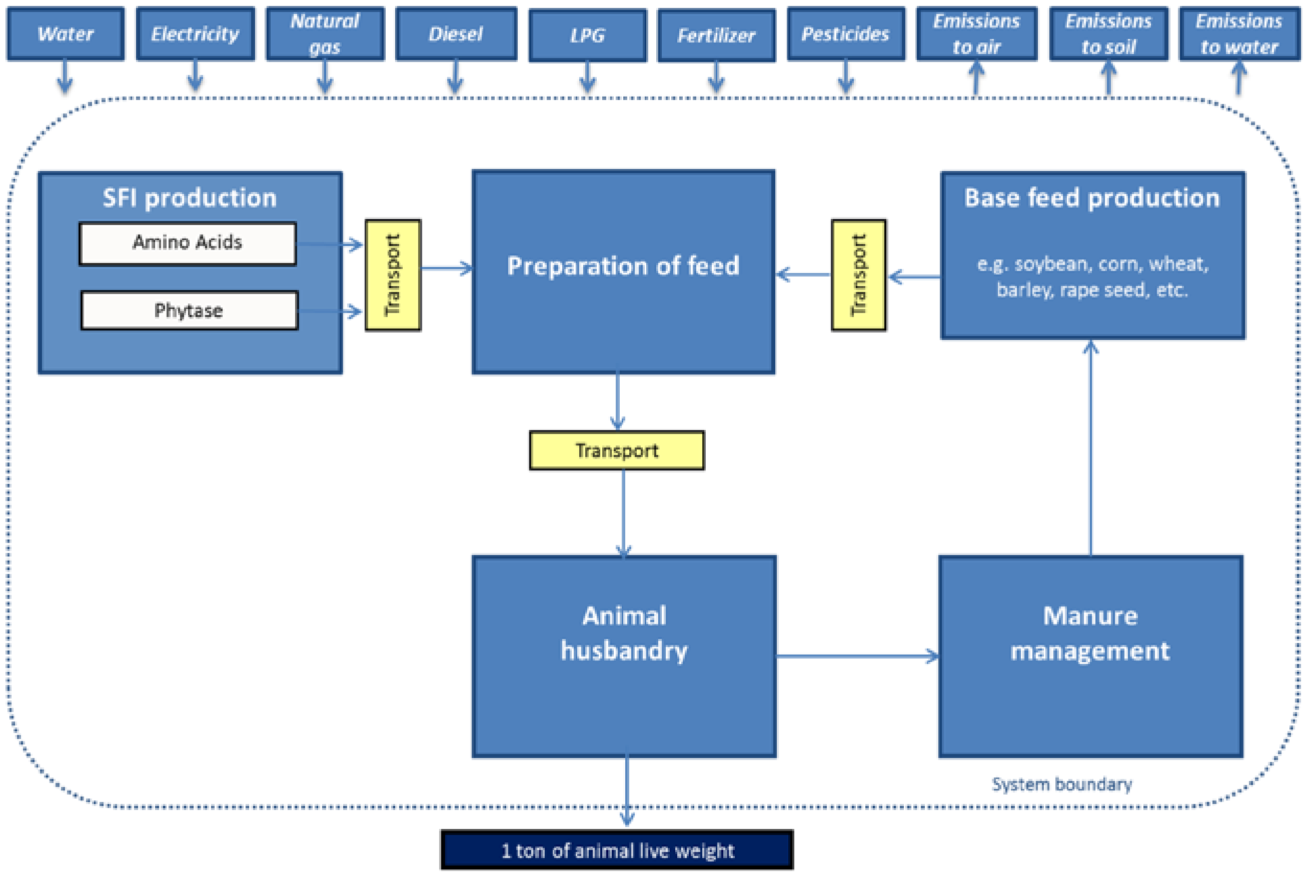

Figure 1. Overview of the system boundary. Subsystems include production of base feed ingredients, specialty feed ingredients (SFI), preparation of feed, animal husbandry, and manure management. LPG = liquefied petroleum gas.

the efficiency of converting feed consumption (kg) to LW production (kg), and the percentage of manure N and P given credit for avoided production of mineral fertilizer (manure N credits). The U.S. National Pork Board reported that feed efficiency in conventional pig production has been decreasing from 2.82 in 2008 to 2.68 in 2012 (National Pork Board, 2014). Therefore, we used a conservative estimate of 2.75 FCR in all alternatives and regions. In broilers the FCR is variable in different alternatives and regions because of the differences in achieving a certain level of FCR on the basis of available feed ingredients (Table 1). In all alternatives (A1 to A3) a 50% manure N credit was applied to make a direct comparison between alternatives.

Partial Sensitivity Analysis

A partial sensitivity analysis was conducted to investigate the influence of FCR and manure credits to overall environmental impact. The FCR is closely linked to level of nutrients; therefore, a change of FCR in a given feeding regime was analyzed to identify further improvements of technology that can potentially affect FCR. The modeling approach for N credits was analyzed to indicate the influence of the approach on the overall results. Therefore, 5 scenarios for each region and each production system were investigated to assess potential improvements in the pig and poultry sectors and their environmental implications (Table S1). The scenarios were only the standard base diet with a higher FCR and 50% manure credits (**S1**), only the standard base diet with lower FCR and no manure N credits (**S2**), the standard base diet supplemented with AA and phytase with lower FCR and 50% manure N credit (**S3**), a diet similar to S3 but with higher FCR and 100% manure credit (**S4**), and a diet similar to S3 with 100% manure credit, considered to be the optimal scenario (**S5**).

Description of Processes

Base Ingredients. The sourcing of base feed ingredients for both production systems varies according to the region under investigation. Additionally, animals are typically fed in phases according to their stage of growth, which might differ slightly in the 3 regions studied. Commercially viable and representative feed compositions for each phase were averaged according to their respective contribution in the growing phase. Six diets were prepared for sows (gestating and lactating phases), weaned pigs (prestarter and starter phases),

Table 1. Description of alternatives (A) analyzed in pig and broiler production systems in Europe, North America, and South America[1]

	A1	A2	A3
Pig production system (Europe, North America, South America)			
AA	−	+	+
Phytase	−	−	+
Feed conversion ratio	2.75	2.75	2.75
Manure N credits	50%	50%	50%
Broiler production system, Europe			
AA	−	+	+
Phytase	−	−	+
Feed conversion ratio	2.01	1.85	1.85
Manure N credits	50%	50%	50%
Broiler production system, North America			
AA	−	+	+
Phytase	−	−	+
Feed conversion ratio	1.80	1.70	1.70
Manure N credits	50%	50%	50%
Broiler production system, South America			
AA	−	+	+
Phytase	−	−	+
Feed conversion ratio	1.80	1.70	1.70
Manure N credits	50%	50%	50%

[1]The alternatives were: (A1) standard base diet only, (A2) standard base diet supplemented with crystalline amino acids only, and (A3) standard base diet supplemented with crystalline amino acids and phytase.

and fattening pig (grower and finisher phases). Diets for sows and weaned and fattening pigs represented 16%, 11%, and 73%, respectively in European conditions and 13%, 9%, and 78% in the Americas, respectively. For broilers in Europe and South America, the prestarter, starter, and finisher diets made up 5%, 25%, and 70% of total growth, respectively. For North America, there were 4 phases, including starter, grower, finisher, and withdrawal diets, making up 5%, 25%, 35%, and 35% of total growth, respectively. Diets for pigs in North and South America were formulated on the basis of NRC (2012). The InraPorc model (Van Milgen et al., 2008) was used to formulate diets for pigs in Europe on the basis of the least cost principle. The average feed and nutritional composition of 1 t of feed for each alternative (A1 to A3) and region formulated are presented in Table 2 for the pig production system and Table 3 for the broiler production system. In the broiler production system, it is challenging to come up with diets that meet the requirement without additional methionine, so the base diet was formulated to meet nutrient requirements, and the supplemented diets were formulated according to least cost principles. Information on databases used for the lifecycle inventory data for production of feed ingredients is given in Supplemental Table S2.

Specialty Feed Ingredients. According to Tokach and DeRouchey (2012), the first limiting AA for pigs are lysine, threonine, and tryptophan, and for broilers, methionine, lysine, and threonine are first limiting. Amino acid requirements were assessed on the basis of standardized ileal digestibility for both pigs and broilers because it represents the best available method for routine evaluation of AA bioavailability in feedstuffs (NRC, 2012). The feeding regimes A2 and A3 in this study were supplemented with lysine, threonine, methionine, and tryptophan (Tables 2 and 3). Apparent fecal digestibility is used to assess P availability for both poultry and pigs. Phytase was supplemented in alternative A3 of this study.

Supplemental AA are mostly produced in 2 ways: 1) chemical synthesis and 2) microbial synthesis using fermentation with AA overproducing microbial strains. Lysine, threonine, and tryptophan are produced through fermentation in stirred-tank reactors (Drauz et al., 2012; Garcia-Launay et al., 2014). Methionine is generally synthesized chemically from ammonia and recovered by crystallization (Drauz et al., 2012). The production of the AA lysine, threonine, and methionine was modeled according to Mosnier et al. (2011) and Garcia-Launay et al. (2014). Tryptophan requires twice as much raw material as needed for lysine or threonine production based on the literature survey by Ikeda (2003). The basic production data to produce lysine, threonine, and methionine are given in Supplementary Table S3.

Most commercially available phytase enzymes are produced from microbial fermentation using fungi (Herbots et al., 2008). Fermentation takes place mostly in an aerobic stirred tank reactor (Chotani et al., 2012). The extracellular enzymes are then recovered from the biomass through centrifugation and filtration. The enzymes are then isolated through filtration, concentration, purification, and drying. The final formulation includes preservation and standardization, which can be achieved through dilution followed by drying (Nielsen et al., 2007). There are currently no life cycle inventory data available for the production of phytase; therefore, input details from Nielsen et al. (2007) were directly transferred and integrated in the GaBi software model (PE INTERNATIONAL AG, 2012). The life cycle impact assessment data for producing phytase is given in Supplementary Table S4.

Feed Preparation. Feed is usually processed in a feed mill before being transported to farm and fed to the animals. Therefore, feed preparation in a feed mill is assumed for this study. According to Pelletier (2008), 137 MJ electricity, 294 MJ thermal energy, and 75 kg water were required for preparation of 1 t of broiler feed (including pelleting). For pigs, 30 kWh or 108 MJ electricity are required for the preparation of 1 t of pig feed without pelleting (personal communication with feed industry representative). Although pelleting is used in North America, especially for nursery pigs, there is a lack

Table 2. Ingredient and nutrient composition of 1 t of average diet for pig system alternatives in Europe and North and South America[1]

Item	Europe			North America			South America		
	A1	A2	A3	A1	A2	A3	A1	A2	A3
Ingredient, kg/t									
Wheat	344	382	379						
Corn	145	143	128	472	640	650	650	751	764
Barley	213	288	311						
Wheat bran	11	22	22				4	4	4
Rapeseed meal	3	54	51						
Soybean meal	232	67	68	251	94	93	273	171	169
Rapeseed oil	7	3	3						
Extruded soybean grain	9	0.1	0.1						
Lysine	0	4	4	0	5	5	0	3	3
Threonine	0	1	1	0	1	1	0	0.3	0.3
Methionine	0	0.4	0.4	0	0.3	0.3	0	0.2	0.2
Tryptophan	0	0.2	0.2	0	0.3	0.4	0	0	0
Phytase	0	0	0.1	0	0	0.1	0	0	0.1
Monocalcium phosphate	7	7	2	3	5	1	10	10	2
Salt	4	4	4	3	3	4	4	4	4
Calcium carbonate	16	16	18	12	13	15	7	7	9
Vitamin premix	5	5	5	5	5	5	7	7	7
Dried whey	3	3	2	2	2	2			
Corn DDGS[2]				146	146	146			
Wheat middling				73	73	68			
Fishmeal				0.4	0.4	0.4			
Plasma protein				0.6	0.6	0.6	3	3	3
Fat				31	12	10	22	18	14
Corn (heat processed)							11	11	11
Sugar							3	3	3
Lactose							7	7	7
Nutrient composition									
CP, g/kg	181	138	138	212	156	156	187	158	158
Total P, g/kg	5.39	5.40	4.39	5.29	5.05	4.12	5.38	4.90	3.90
ME, kcal/kg	3,107	3,026	3,027	3,402	3,321	3,321	3,236	3,236	3,236
Digestible lysine	7.83	7.80	7.80	8.68	8.51	8.51	8.28	7.98	7.98
Digestible methionine	2.50	2.39	2.38	3.06	2.87	2.70	2.67	2.55	2.54
Digestible threonine	5.60	5.25	5.25	6.34	5.55	5.39	6.05	5.55	5.52
Digestible tryptophan	1.95	1.57	1.57	2.09	1.78	1.62	1.80	1.63	1.65

[1]The diet is an average for sows, weaned, and fattening pigs. In Europe, reproductive, weaning, and fattening phases constituted 16%, 11%, and 73%, respectively. In North and South America the phases constituted 13%, 9%, and 78%, respectively. The values applied in the alternatives are related to feed intake for the production of 1 t live weight. The alternatives were A1, only standard base diet; A2, standard base diet supplemented with only crystalline AA; and A3, standard base diet supplemented with crystalline AA and phytase.

[2]DDGS: distillers dried grains with solubles.

of data, and its contribution to the total feed consumed is marginal, so it was not included in the analysis. These values were used to estimate the energy requirement of the feed mill for preparation of broiler and pig feed for all alternatives, scenarios, and regions. Because the composition of compound feed varies between the different stages of production per species, the feed under investigation was a representative weighted average over the whole production cycle to simplify the calculations.

Animal Husbandry. All animal husbandry systems analyzed in this study were conventional systems representing the typical production system of each region. The animal husbandry process requires energy in the housing facilities, i.e., electricity for lighting, cooling, ventilation, and feed distribution, as well as thermal energy for heating. The specifications of input parameters for animal production for the 3 regions are given in Supplementary Tables S5 and S6 for pig and broiler production systems, respectively. Enteric methane emissions are considered as part of the animal housing and calculated from feed digestible fiber content according to Rigolot et al. (2010).

Manure Management. Animal excretion, manure storage, and field application leads to N- and carbon-based emissions to air, such as methane, nitrous oxide,

Table 3. Ingredient and nutrient composition of 1 t of average diet for broiler system alternatives in Europe and North and South America[1]

	Europe			North America			South America		
Item	A1	A2	A3	A1	A2	A3	A1	A2	A3
Composition, kg/t									
Wheat	0	454	454						
Corn	392	242	242	554	623	618	497	684	693
Wheat bran	28	0	0						
Rapeseed meal	78	18	18						
Soybean meal	449	223	223	283	221	238	273	271	270
Rapeseed oil	20	20	20						
Lysine	0	3	3	0	2	2	0	2	2
Threonine	0	0.7	0.6	0	0.6	0.6	0	0.3	0.2
Methionine	0	2	2	0	3	3	0	2	2
Phytase	0	0	0.1	0	0	0.2	0	0	0.1
Monocalcium phosphate	11	11	7						
Salt	4	4	4	2	1	2	5	4	4
Sodium bicarbonate	0	0.4	0.4						
Calcium carbonate	15	18	22	5	5	12	8	8	8
Vitamin premix	5	5	5	2	2	2	5	5	5
Corn DDGS[2]				64	64	64			
Meat meal (55%)				52	52	30			
Defluorinated phosphate				3	3	0.2			
Sulfur carbonate				2	1	2			
Soybean oil				33	21	25	0	11	8
Corn gluten							200	0	0
Dicalcium phosphate							12	12	7
Nutrient composition									
CP, g/kg	265	179	179	219	199	195	293	187	187
Total P, g/kg	7.29	6.10	5.10	6.0	5.9	4.6	5.14	5.61	4.78
ME, kcal/kg	2,831	3,082	3,082	3,124	3,124	3,124	3,047	3,047	3,047
Digestible lysine	13.4	9.70	9.70	9.65	9.51	9.98	9.08	9.97	9.97
Digestible methionine	3.74	4.38	4.38	3.05	5.71	5.82	3.32	4.74	4.75
Digestible threonine	9.19	6.30	6.30	6.39	6.09	6.38	6.58	5.94	5.84
Digestible tryptophan	2.81	1.85	1.85	2.09	1.75	1.85	1.93	1.85	1.85

[1]The diet is an average for prestarter, starter, and finisher broilers. The values applied in the alternatives are related to feed intake for the production of 1 t live weight. In all regions, the prestarter, starter, and finisher phases constituted 5%, 25%, and 70%, respectively. The alternatives were A1, only standard base diet; A2, standard base diet supplemented with only crystalline AA; and A3, standard base diet supplemented with crystalline AA and phytase.

[2]DDGS: distillers dried grains with solubles.

and ammonia, and water, such as nitrates and phosphates (Environmental Protection Agency, 2011). Methane emissions from manure were calculated according to the Intergovernmental Panel on Climate Change (**IPCC,** 2006). Ammonia and nitrous oxide emissions were calculated on the basis of Jarvis and Pain (1994), IPCC (2006), Rigolot et al. (2010), and Dämmgen et al. (2013). Emission factors and rates of emissions from pig and broiler manure storage and field application are given in Supplementary Table S7.

Besides emissions, manure generates a benefit to the system by providing essential nutrients for cash and feed crops. For manure applied on the field a credit is given according to the amount of N, phosphate, and potassium available for plant uptake. Nitrogen and P excretion was calculated as the difference between uptake and retention of N and P in broilers. The model of Rigolot et al. (2010) was used for N and P excretion in pigs. The uptake is calculated on the basis of the CP/total P content in the animal feed, final weight, and the FCR. Manure was assumed to be applied by the farmer to virtual fields that could be the feed ingredient fields but also cash crop fields or other arable land. Average emission factors to air and water based on IPCC (2006) were assumed for manure applied on land. By taking into account the mineral and organic fertilizer used in base feed ingredient production and the application of the manure on the farm fields (e.g., of self-produced base feed ingredients) a double accounting of some parts of the nutrients and its emissions takes place. To eliminate the double accounting, a credit for avoided nutrient field application (including occurring emissions, i.e., leaching to water of mineral fertilizers, which was calculated with the respective emission factors) and fertilizer production is given. The credit given was based on the manure nutrients that were actually available after subtraction of emissions to air and water during storage and field application (Nguyen et al., 2010). Although Nguyen et al. (2010) recommend using 75% for manure N credit, a more conservative approach of 50% is used in all alternatives and regions. Because of concern of P loading in the environment, a smaller amount of manure N maybe applied than the crop requirement. This number should be adjusted if information from a specific country or region is available.

Land Use Change. Land conversion for production of crops used as animal feed is of a major interest as fertile land is a scarce resource (FAO, 2010). Direct land use change (**dLUC**) has impacts on the environment through GHG emissions and changes in biodiversity and soil quality, which needs to be taken into account in an LCA study. In South America, soybean production has substantially increased over the last few years, and part of the production area increase is based on dLUC, which was calculated on the basis of national area statistics. Therefore, the study considers impact of land use change for soybean production in South America. The global warming potential impacts from dLUC of the different crops in the respective regions under investigation were calculated according to British Standards Institution (2012) methodology. For example, wheat, maize, and rapeseed in Europe had emissions of 0.03, 0.04, and 0.1 t CO_2 equivalent (**CO_2 eq**)/t crop, respectively. On the basis of Flynn et al. (2012), an average annual land use change emission factor of 34.8 t CO_2 eq/ha for South America was applied. The emissions from dLUC per hectare soybeans cultivated were calculated by multiplying the emission factor of South America with the area applicable to dLUC. This calculation resulted in annual dLUC emissions of 18.4 t CO_2 eq/ha for soybeans cultivated in Brazil. With estimated annual yield of 2.7 t/ha, 1 kg of soybeans bears an environmental impact of 6.8 kg CO_2 eq/kg, which leads to global warming impacts of 6.2 kg CO_2 eq/kg of soybean meal and 16.1 kg CO_2 eq/kg of soybean oil.

In addition to the dLUC covered in the study, there is also a debate on the consideration of so-called indirect land use change factors into environmental assessments. However, the inclusion of indirect land use change is not required by ISO 14040 and ISO 14044. Indirect LUC factors were excluded from the scope of the study because of their large uncertainties and inconsistency with international LCA standards (Finkbeiner, 2014b).

Phosphorus. Phosphorus loading in the environment occurs because of leaching and soil erosion. As plants and crops take up P, the deficit has to be addressed by adding fertilizers. Manure and mineral fertilizers are used to supply P for the plants. However, when too much fertilizer is applied, the soil cannot hold increasing amounts of insoluble phosphate without its concentration growing over time (Bomans et al., 2005). This increases the risk that phosphate will be lost via soil runoff or leaching through the soil. For this study, P emissions were modeled on the basis of Nielsen et al. (2007). Furthermore, P reserves are finite; hence, losses not only cause environmental damage but also waste a depleting resource (Kebreab et al., 2012).

Life Cycle Inventory Analysis

The functional units for the 2 production systems in this study were 1 t LW pigs and 1 t LW broilers at the farm gate. Use of SFI was considered not to have an impact on the further processing performance of the animals. Data for upstream and downstream materials and processes were obtained from the GaBi database (PE INTERNATIONAL AG, 2012). The N provision to calculate manure credits was covered by a urea data set, whereas P provision was covered by a triple superphosphate data set from the GaBi database (PE INTERNATIONAL AG, 2012).

The Centre of Environmental Science at Leiden impact assessment methodology framework (version 3.9, November 2010) was selected for this assessment because it is the most commonly used method and facilitates comparison with other LCA studies (Guinée et al., 2002). The environmental indicators or impact assessment categories considered in this study were global warming potential (**GWP**), eutrophication potential (**EP**), acidification potential (**AP**), and primary energy demand fossil (**PED**) as they are the most common impact categories associated with livestock (De Vries and de Boer, 2010). Global warming potential and PED were chosen because of their relevance to global climate change and to energy and resource efficiency, which are strongly interlinked, of high public and institutional interest, and deemed to be some of the most currently pressing environmental issues. Eutrophication potential and AP were chosen because they are closely connected to air, soil, and water quality and capture the environmental impact associated with commonly regulated emissions.

The GaBi database was used for all chemical refinery products. Animal feed, materials, and chemicals needed during manufacturing were modeled using the allocation rule most suitable for the respective product, which is given in the next section for the major base crops in the study. Most of the data for model input and parameters were collected on the basis of publically available literature and existing studies. The sources for fuel and energy and raw materials and processes were taken from the GaBi database (PE INTERNATIONAL

AG, 2012) calculated for each region. Average transportation distances and modes of transport were included for the transport of the base feed ingredients and SFI to the feed mill and from the feed mill to the animal housing. Details of transport distances and modes of transport applied in the different regions studied are summarized in the supplemental information (Table S8).

Allocation Rules and Choice of Base Ingredients

In European pig and broiler production, wheat, corn, barley, wheat bran, rapeseed, and soybean meal as well as rapeseed oil and extruded soybean grains constitute the main ingredients (Mosnier et al., 2011). Data from Eurostat (2015) show that the main ingredients, except soybean, are grown in Europe. The main ingredients in North America for pig and poultry production are corn and soybeans. According to FAOSTAT (FAO, 2014), the United States produces 321 Mt corn and 88 Mt soybeans annually. Pig and broiler diets in South America are similar to those in North America and are based on corn and soybeans. Brazil and Argentina produce 75 Mt of corn and 102 Mt of soybeans (FAO, 2014).

The U.S. production of soybeans and corn is assumed to cover the entire demand for livestock feed in North America. The following assumption and allocation rules apply for base ingredients based on the GaBi database (PE INTERNATIONAL AG, 2012). Intensive cultivation of corn is modeled assuming a 20-ha plot of land. The yield applied in the model is 9 t corn/ha. Corn is typically cultivated in a rotation with soybeans at a ratio of 1:1. The intensive cultivation of soybeans is modeled assuming 20-ha land plots and yield of 3 t/ha. Soybeans are supplied with N fertilization only if inoculation with mycorrhiza fails. In South America, soybeans are usually grown in rotation with other crops, including oats, wheat, green manure crops, and maize, depending on the region. Soybeans consume almost no N fertilizer, and the total balance between N exported in grain and provision from the ground is negative.

The intensive cultivation of winter wheat on a 5-ha plot of land is modeled with a yield of 8.9 t/ha. Wheat is typically cultivated using combined systems; crop rotation with sugar beets and winter barley is applied. The harvest of grain and straw is done by combining. An allocation by market prices between grain and straw is applied. The spring barley cultivation is modeled assuming a yield of 5 t/ha. An allocation based on market price is also applied between grain and straw.

Assumptions and Limitations

The results of this assessment are limited to only the defined goal and scope, and exclusion of certain life cycle impact categories may result in an incomplete picture of the overall performance of the studied products. For instance, social and economic indicators were not covered in this LCA, so trade-offs between environmental, social, and economic factors were not evaluated. There is natural animal-to-animal variability in performance, but this study assumes an average performance. Because of data availability for vitamins and trace elements, the values for citric acid were used as an approximation for estimating environmental impacts from these ingredients.

The geographical boundaries of the production systems were very broad. Although the data sets were chosen to be representative and the best fit to geographical boundaries, results for specific countries within the regions are likely to deviate from the findings presented in this study. A subregional approach within the 3 continents represented would increase accuracy but would also pose even greater challenges with regard to data availability. Regional boundaries for electricity and fuel usage for North and South America were set to U.S. and Brazilian conditions, respectively, because they constitute the majority of production within the given regions. For European conditions feed information from mostly Germany were used. Animal housing conditions were based on literature data and may be improved by primary data collection. The data used for the analysis were taken mostly from existing data sets. Because of the above limitations care should be taken in applying results to specific countries within the regions covered in the study.

RESULTS

In this section the main results for each of the above mentioned environmental indicators and impact assessment categories associated with pig and broiler production in Europe, North America, and South America for each alternative are presented. Results of the partial sensitivity analysis are also given.

Europe

Global Warming Potential. In Europe, feed production contributes the greatest amount to GWP in both pig (49% to 54%) and broiler (52% to 53%) production systems (Fig. 2). If dLUC is considered, the importance of feed production for the 2 types of livestock becomes even greater (Fig. 2). For pigs, the impact of feed production in unsupplemented (A1) was lower than in supplemented (A2 and A3) alternatives. In contrast, for broilers, feed production had greater impact in A1 compared to A2 and A3. Although for both livestock categories transportation processes had a moderate impact on the GWP (6% to 9%), supplemented alternatives had lower GWP because fewer soybeans were calculated to be shipped from South America to Europe. In pig and broiler production systems, alternative A3 had the lowest GWP (1.98 and 1.34 t CO_2 eq/t LW, respectively).

Eutrophication Potential. Manure field application was the most important driver of results associated with EP for pigs (48% to 52%) and broilers (51% to 61%), followed by feed production, which contributed 26% to 44% and 19% to 40%, respectively (Fig. 2). Emissions from manure storage were also important contributors to EP in pigs (28% to 38%) and broilers (14% to 20%). In pigs, the impact of manure field application in supplemented alternatives was about 31% and 33% lower than for A1, respectively. In broilers, A1 had about 51% greater EP compared to A2 and A3. Although for both livestock categories transportation processes had a low impact (2% to 3%) on the EP, fewer soybeans were shipped from South America to Europe in A2 and A3, with slightly lower EP impact from transportation. In both pig and broiler production systems, A3 had the lowest EP (11.5 and 12.5 kg PO4 eq/t LW, respectively).

Acidification Potential. The greatest contributors to AP in both species were manure storage (55% to 65%) and manure field application (21% to 29%; Fig. 2). Transportation played a minor role for both livestock categories (3% to 6%). The impact of manure storage in A2 and A3 was about 31% lower than in A1 for pigs and 51% lower for broilers. There was less AP due to transport in A2 and A3 because fewer soybeans were shipped from South America to Europe compared to A1. The lowest AP in pigs and broilers was alternative A3 (33.3 and 45.3 kg SO_2 eq/t LW, respectively).

Primary Energy Demand. The greatest PED in pigs and broilers was from feed production (62% to 76% and 49% to 50%, respectively) and animal housing (19% to 23% and 24% to 27%, respectively; Fig. 2). In pigs, the impact of feed production in A2 and A3 was about 8% and 5% greater than in A1, respectively. In contrast, the PED of A2 and A3 in broilers was about 8% lower than that of A1. In broilers, the feed mill, hatchery, and transportation accounted for 24% to 26% of the PED. In pigs A1 had the lowest PED (12.5 GJ/t LW), but in broilers it was A3 (13.8 GJ/t LW).

North America

Global Warming Potential. Feed production was the most important contributor to GWP in pig and broiler production systems (51% to 56% and 60% to 61%, respectively; Fig. 3). Animal housing was also significant for both livestock categories. Land use change emissions were not relevant because feed was not expected to be sourced from South America. In both species, although the GWP impacts of all alternatives were similar, GWP from feed production in A1 was slightly lower than in A2 and A3. Alternative A3 had the lowest GWP, with 2.15 t CO_2 eq/t LW in pigs and 1.31 t CO_2 eq/t LW in broilers. MacLeod et al. (2013), in a FAO report, showed greater pig and broiler emission intensities globally compared to our results, but the methodology of accounting was not the same. However, like us, they also reported greater emission intensities from South America, followed by Europe and North America.

Eutrophication Potential. Manure field application was the most important driver of EP in pigs and broilers (51% to 54% and 43% to 47%, respectively; Fig. 3), followed by manure storage (28% to 38%) in pigs and feed production in broilers (35%–42%). In pigs, the EP impacts of manure field application in A2 and A3 were about 33% and 35% lower than in A1, respectively. In broilers, A2 and A3 had 19% and 27% lower EP than A1, respectively. In both species, A3 had the lowest EP, with 13.7 kg PO4 eq/t LW in pigs and 14.5 kg PO4 eq/t LW in broilers.

Acidification Potential. The greatest driving forces of AP in pigs were manure storage (55% to 65%) and manure field application (21% to 30%; Fig. 3). In contrast, the greatest drivers of results associated with AP in broilers were manure field application (56% to 61%) and storage (28% to 30%; Fig. 3). For pigs, the AP impact of manure storage in both AA supplemented alternatives A2 and A3 was 70% lower than in A1. Similarly, the AP impacts of manure field application in A2 and A3 were 21% to 25% lower than in A1. Alternative A3 had the lowest AP, with 41.4 kg SO_2 eq/t LW in pigs and 45.0 kg SO_2 eq/t LW in broilers.

Primary Energy Demand. The greatest PED was from feed production (74% to 81% and 60% to 62% in pigs and broilers, respectively; Fig. 3). In pigs, the PED impact of feed production for A2 and A3 was 13% and 11% greater than for A1; however, there were only minor differences in broilers among all alternatives. The feed mill, transportation, and hatchery accounted for 8% to 20% of the overall PED in broilers. Alternative A1 had the lowest PED of 14.3 GJ/t LW in pigs, whereas in broilers A3 had the lowest PED, with 13.8 GJ/t LW.

South America

Global Warming Potential. In South America, GWP was mainly influenced by feed production for pigs and broilers (68% to 71% and 62% to 71%, respectively; Fig. 4). In both species, the contribution from feed production was greater when dLUC was considered (Fig. 4). For pigs, the impact of feed production was similar in all alternatives, whereas in broilers A2 and A3 both had about 30% lower GWP than A1. Alternative A3 had the lowest GWP, with 2.46 t CO_2 eq/t LW in pigs and 1.12 t CO_2 eq/t LW in broilers.

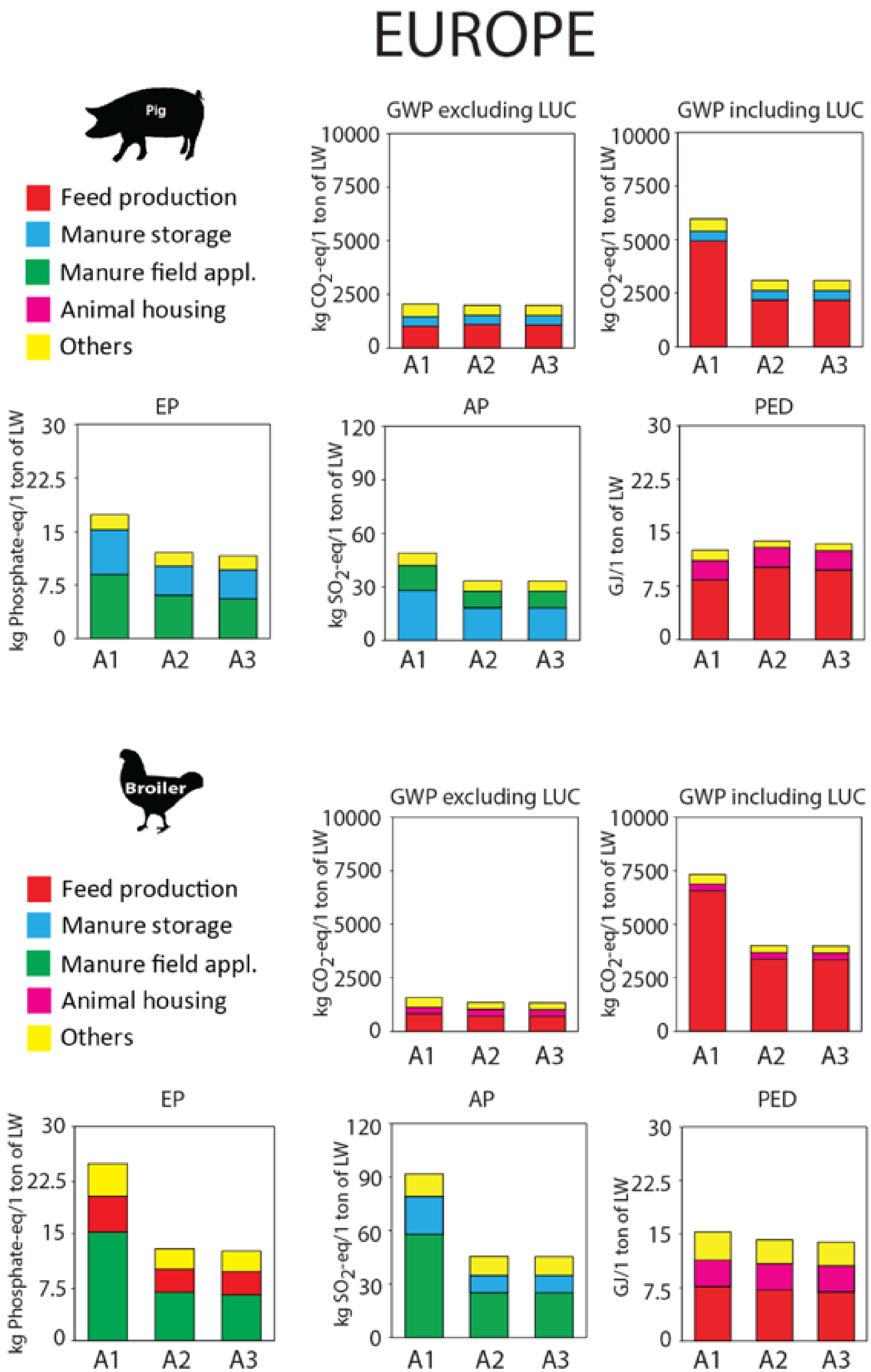

Figure 2. Estimates of impact assessment categories in European pig and broiler production systems. The alternatives were A1, only standard base diet; A2, standard base diet supplemented with only AA; and A3, standard base diet supplemented with AA and phytase. GWP = global warming potential; LUC = land use change; EP = eutrophication potential; AP = acidification potential; PED = primary energy demand. In the legend, "Others" includes transportation, feed mill, hatchery, and manure credits (negative value).

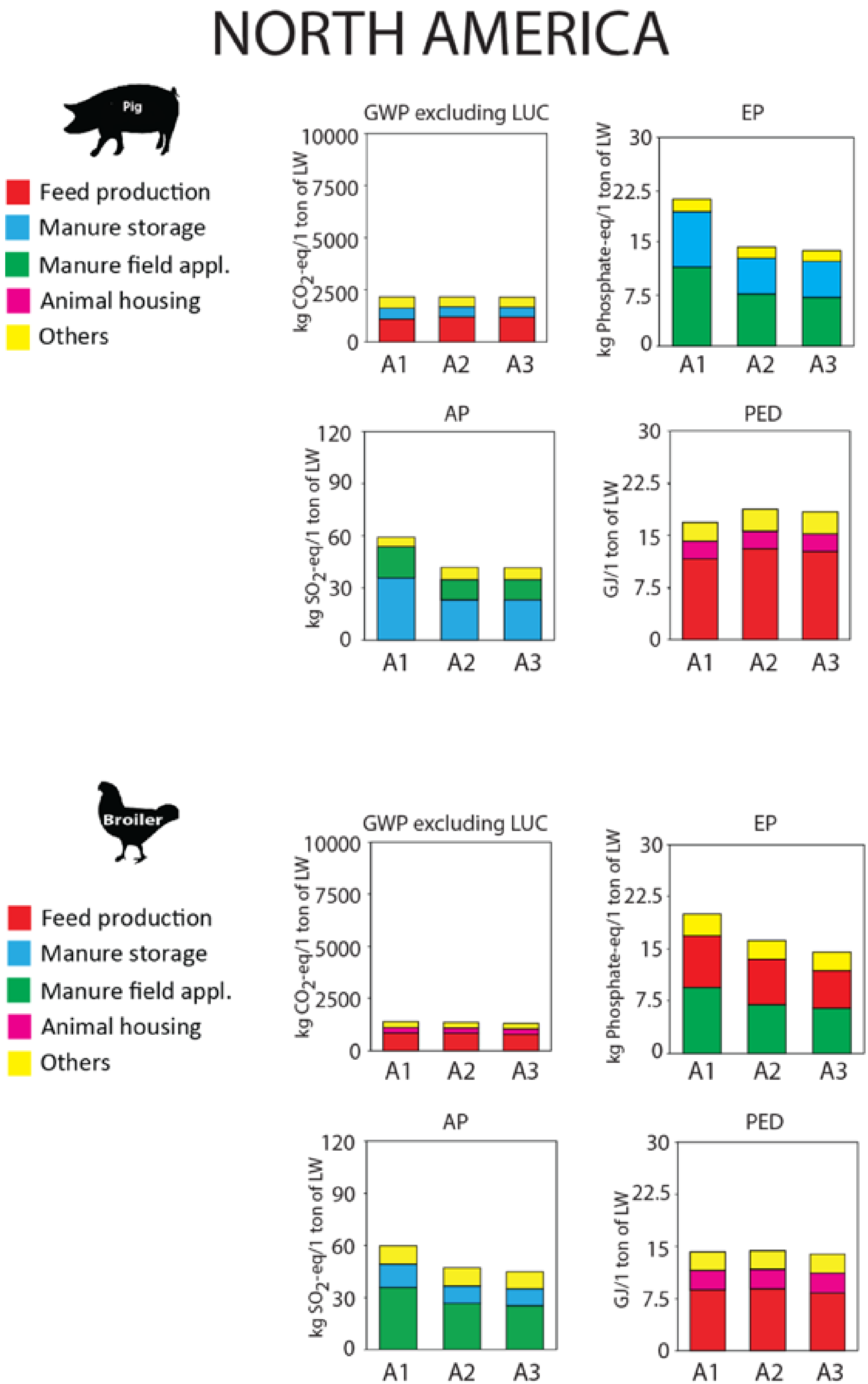

Figure 3. Estimates of impact assessment categories in North American pig and broiler production systems. The alternatives were A1, only standard base diet; A2, standard base diet supplemented with only AA; and A3, standard base diet supplemented with AA and phytase. GWP = global warming potential; LUC = land use change; EP = eutrophication potential; AP = acidification potential; PED = primary energy demand. In the legend, “Others” includes animal housing, transportation, feed mill, hatchery, and manure credits (negative value).

Eutrophication Potential. Manure field application was the most important driver for EP in pig and broiler production systems (40% to 45% and 50% to 63%, respectively), followed by manure storage (27% to 33% and 16% to 20%, respectively; Fig. 4). For pigs, feed production also played an important role (33% to 53%). Compared to A1, the EP impact of manure field application in A2 and A3 pigs was about 20% and 23% lower, respectively, whereas in broilers it was 48% and 49% lower, respectively. Alternative A3 had the lowest EP, with 15.6 kg PO4 eq/t LW in pigs and 11.8 kg PO4 eq/t LW in broilers.

Acidification Potential. The greatest contributors to AP in pig production systems were manure storage (45% to 51%) and feed production (23% to 35%; Fig. 4). In broilers, manure field application (55% to 65%) and manure storage (21% to 24%) were the greatest contributors (Fig. 4). In pigs, manure field application also played an important role (23% to 25%). Compared to A1, the AP impact of manure storage in both A2 and A3 was 30% lower in pigs, whereas in broilers, the AP impact of manure field application in A2 and A3 was 53% lower. In pigs and broilers, A3 had the lowest AP, with 44.9 and 40.6 kg SO_2 eq/t LW, respectively.

Primary Energy Demand Fossil. The greatest PED in pig and broiler production systems was from feed production (88% to 93% and 65% to 79%, respectively; Fig. 4). Animal housing was also an important contributor (14% to 21%) in broiler production, followed by the feed mill, transportation, and hatchery, which together accounted for 8% to 20% of the total PED. All alternatives had a comparable PED from feed production in the pig system; however, in broiler production, alternatives A2 and A3 had 32% and 34% lower PED from feed production compared to A1. The lowest PED in pig production was A1, with 17.5 GJ/t LW, whereas in broiler production it was A3, with 9.9 GJ/t LW.

Partial Sensitivity Analysis

There was only a slight difference in GWP impact between S1 and S2 scenarios in pigs in all regions, indicating that lower FCR compensated for manure credits. However, if dLUC was included, lower FCR reduced GWP impact more than manure credit because of a lower feed requirement, in particular imports of soybeans from South America (Fig. S1–S3). In supplemented scenarios, GWP impact was more sensitive to reduction in FCR compared to increased manure credit in both broiler and pig production systems. The main differences were due to GWP impact in feed production.

In pigs, unsupplemented scenario S1 had lower EP impact than S2 in all regions. This is due to the greater manure credit in S2. Although lower FCR in S2 meant less feed was required, more of the EP impact was reduced by manure credits for avoided application and production of mineral fertilizer. In broilers, S1 had greater EP impact because although there is a manure credit, because of a higher FCR, much more feed is required, which resulted in greater quantities of manure that need to be stored and later applied (Fig. S1 to S3). In supplemented scenarios for both pigs and poultry, FCR was more important than manure credits as S4 had a slightly higher EP impact than S3 and S5. Among all scenarios, S5 had the lowest EP because of a combination of better FCR and greater manure credits.

Specialty feed ingredient unsupplemented scenarios S1 and S2 had similar AP impacts in all regions for the pig production system. The differences mainly arose from emissions during manure storage and manure field application. Although fewer emissions were calculated for S2 from manure because of the lower volume produced, the lack of a manure credit brought the emissions to a level similar to that in S1 (Fig. S1 to S3). However, in broilers even in the absence of manure credits, lower FCR had a considerable influence on reducing AP impact. This trend was also apparent in all regions and both production systems, where greater FCR led to greater manure production and AP impact.

In unsupplemented pig production system scenarios, S1 had slightly lower PED than S2 (Fig. S1 to S3). The differences mainly arose from PED in feed production, animal housing, and manure credits. In broiler systems PED in the hatchery also played a role, with S1 and S2 having similar PED impacts. In supplemented scenarios, S4 had the greatest PED compared to S3 and S5, mainly because of the higher energy required for feed production and the hatchery (in broilers). In both pig and broiler systems, the primary energy credits for avoided production and application of mineral fertilizer were also relevant, reducing total S5 PED by 10% and 7%, respectively.

DISCUSSION

The environmental impacts of using supplemental AA and phytase were assessed using well-established LCA methodology. The life cycle impact assessments were grouped in 4 categories as outlined above, and here we provide a discussion of the use of SFI vis-à-vis potential environmental impact groups in the 3 regions of the world included in the study.

Global Warming Potential

Generally, in pig production systems there were minor differences for GWP impact in all 3 regions studied for all alternatives. The amount of feed required

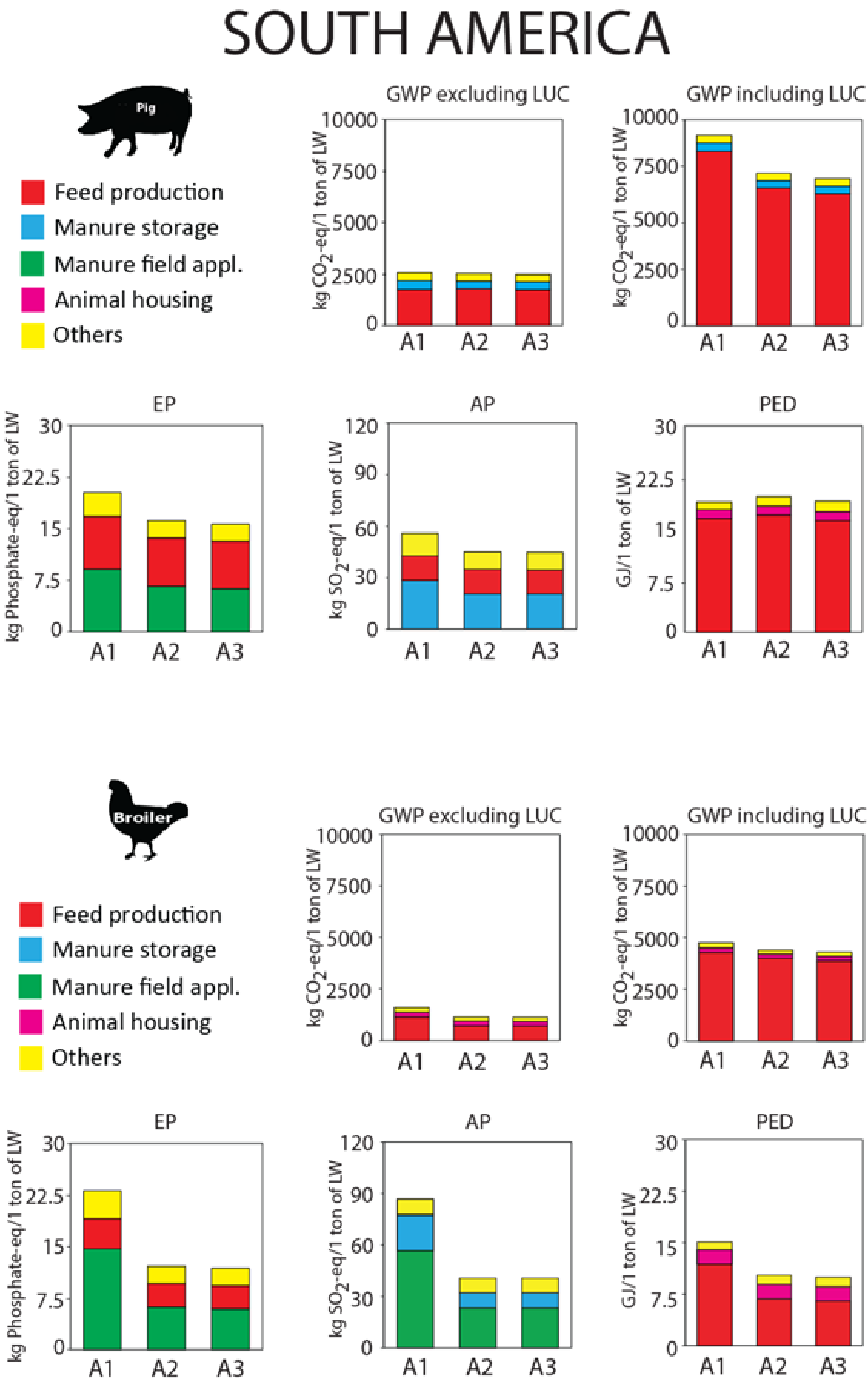

Figure 4 Estimates of impact assessment categories in South American pig and broiler production systems. The alternatives were A1, only standard base diet; A2, standard base diet supplemented with only AA; and A3, standard base diet supplemented with AA and phytase. LUC = land use change. GWP = global warming potential; LUC = land use change; EP = eutrophication potential; AP = acidification potential; PED = primary energy demand. In the legend, "Others" includes animal housing, transportation, feed mill, hatchery, and manure credits (negative value).

was unchanged in all alternatives because FCR was the same. The similar GWP impact was because although N-based emissions during manure storage decreased in both supplemented alternatives, methane emissions increased because of the greater volatile solid content of manure. The reduced feed requirement led to lower GWP from feed production as well as storage and field application because of lower N content of manure.

In broilers, even without consideration of direct dLUC effects, supplemented feeding strategies resulted in considerable environmental improvements for GWP. Feed production was greater in unsupplemented feed because methionine requirements were met with consumption of a greater amount of protein. It is challenging to formulate broiler diets without crystalline AA. The USDA National Organic Program (USDA, 2015) contains an exception regarding DL-methionine and its analogs in organic poultry production with a limit to the maximum levels of crystalline methionine per ton of feed to address this issue. Higher feed consumption in alternative A1 led to higher N excretion and greater environmental cost in manure field application. The potential levels of GWP with supplementation would be 85%, 94%, and 70% of unsupplemented alternative in Europe, North America, and South America, respectively. In agreement with our study, feed production was a major contributor to GWP in British broiler (Leinonen et al., 2012) and Portuguese pig (Gonzalez-Garcia et al., 2015) production systems.

When emissions from dLUC were considered in Europe and South America, large differences in GWP between unsupplemented and supplemented alternatives were apparent in both systems. The GWP increased by up to 2.9 to 4.7 times in Europe and 3.6 to 3.9 times in South America in pig and broiler production, respectively. Using SFI can reduce total GWP in the European pig production system by 52% and by 80% in South America because fewer soybean products are required. Soybean production has been associated with more recent (within 30 yr) deforestation (Macedo et al., 2012). Therefore, dLUC emissions from soybean products from South America considerably change the relative contributions to GWP in both livestock categories (for the European and South American regions). Without LCA, traditional accounting for GWP would have attributed all emissions related to soybean production to South America, excluding emissions due to international trade. As a consequence, European production would seem more sustainable if emissions for soybean production were attributed only to South America (Peters et al., 2012; Caro et al., 2014a). Because of the high emissions from LUC, the methodology used and the assumptions made to calculate the carbon footprint of feed ingredients, particularly soybeans, have a big impact on estimates of emissions. Meul et al. (2012) conducted a sensitivity analysis of European pig diets and showed that dLUC values have a considerable impact on the calculated carbon footprint of different diets. In this analysis the calculated dLUC emissions from a kilogram of soybeans in South America were 20% lower than those reported by FAO (2010). Recently, the Livestock Environmental Assessment and Performance Partnership (**LEAP**, 2015) published guidelines for environmental performance of animal feed supply chains and recommended methodology published by the British Standards Institute, which is similar to what was used in this paper. The main difference between our approach and LEAP (2015) is the data sets for emissions intensities and the life cycle inventory for some crops such as corn, wheat, barley, and soybeans.

Eutrophication Potential

Ammonia emissions to air and nitrate and phosphate emissions to water were the predominant drivers for EP. In both livestock production systems there was a considerable reduction in EP due to the use of SFI. Saving N due to the use of supplemental AA in A2 and A3 led to less excretion of nitrogenous compounds and, consequently, a reduction in EP from ammonia emissions, manure storage, and field application in both animal production systems. In British broiler systems Leinonen et al. (2012) reported that manure constituted a relatively high eutrophication potential, similar to what was observed in this study. There was minimal reduction of EP due to the use of phytase (A2 vs. A3) because nitrogenous compounds dominated their contribution to eutrophication. Phytase supplementation reduced total EP by 3% in pigs and up to 8% in broilers. The effect of phytase was minimal, partly because the analysis assumed the soil's P content did not exceed the capacity for crop uptake, and thus, the reduction of phosphate in the manure was compensated by the use of mineral fertilizers. Therefore, in regions with high soil P, the impact of phytase may be greater than calculated in this study. Ammonia was one of the most important gases reduced by supplementation, and in agreement with several studies, reducing protein content in feed is the most important mitigation option to improve sustainability of animal production (NRC, 2012; Snyder et al., 2014). In a recent LCA study, De Vries et al. (2015) suggested that mitigation actions such as segregation of urine and feces inside housing, addition of zeolite to solid manure, and sealed storage in integrated manure management systems reduced ammonia and methane emissions.

Acidification Potential

The AP of supplemented feeding strategies was 70% to 80% of the unsupplemented alternatives in the pig production system and 47% to 79% in the broiler system. In pig production systems, the AP was heavily influenced by manure storage (41% to 61%), field application (23% to 30%), and feed production (11% to 32%) in all regions. In the broiler production system, manure field application contributed more than storage (55% to 65% vs. 21% to 24%) because broiler manure, unlike pig manure, contains lower ureic acid (Sommer and Hutchings, 2001), the hydrolysis of which is responsible for more than 60% of ammonia production (Mohan and Kovilpillai, 2012). Therefore, ammonia emissions due to this chemical process mainly occur in the later application phase. In this context, for broiler manure, reducing time of exposure on the surface of the ground is the most effective strategy for decreasing ammonia emissions due to manure (Ndegwa et al., 2008). Manure was also reported to be the main component of AP in British broiler systems (Leinonen et al., 2012). Irrigation and tractor operations are sources of nitrogen oxides, which together with ammonia contributed the most to AP. Supplementation with AA reduced N in the feed and excreta, leading to reduced ammonia emissions. Peters et al. (2011) suggested that reducing the leaching of soil N coming from manure might be the best way to balance the N budget without causing acidification. The minor difference in AP between A2 and A3 was due to the reduction in monocalcium phosphate, which is produced from burnt chalk (CaO) and phosphoric acid contributing to AP. Therefore, diets with less monocalcium phosphate (with the addition of phytase) reduce AP. An about 2 to 3 times reduction in AP was possible in both livestock systems by using SFI.

Primary Energy Demand Fossil

In pig production systems, the PED in all regions and alternatives did not show large variability. The PED was influenced by feed and SFI production and animal housing. Similarly, Leinonen et al. (2012) also found that feed production contributed greatly to primary energy use, along with processing and transport, in British broiler systems. The feed mill, transportation, and hatchery (in broiler systems) were also important contributors. The slightly higher trend for PED in supplemented alternatives in pig production systems was due to greater nonrenewable energy use in the production of SFI . In broiler production systems transportation had a relatively greater contribution, and the reduction in PED for supplemented alternatives was due to reduced use of soybeans, which led to lower transportation demand. The greater PED for unsupplemented alternative in South America was because corn gluten had to be used to meet animal nutrient requirement, which was substituted with supplemental AA in A2 and A3.

General Discussion

Supplementation of diets with SFI marginally reduced GWP; however, in pig production systems, there was a substantial advantage to using SFI in Europe and South America when dLUC was taken into consideration. Broiler production systems showed GWP improvements even without dLUC in Europe and South America. Using FAO (2014) data, if SFI were not used, this study estimates that in 2012, GHG emissions due to pig and broiler production systems would have been up by 56% and 54% in Europe, 17% and 15% in North America, and 33% and 19% in South America, respectively. Overall, for the 3 regions analyzed, 127 Mt CO_2 eq associated with pig production and 9.4 Mt CO_2 eq for broiler production were saved in 2012. On the basis of the projections of Alexandratos and Bruinsma (2012) for pig and poultry production for 2050, the use of SFI is expected to save an additional 10 Mt CO_2 eq by the year 2050. Supplementation of animal diets with SFI was beneficial for impact categories AP and EP in both pig and broiler production systems in all regions studied. This is mainly because supplementation reduced protein and P intake and excretion of N and P to the environment (Hou et al., 2014). Primary energy demand was not improved by the use of SFI in pig production in any of the regions, but in broiler systems, PED was reduced in Europe and South America. The effect of phytase in all impact categories was limited. This could be due to the hypothesis taken for the evaluation. More farm-specific models of P utilization and P stored in soil are necessary to evaluate the local impact of phytase on EP. However, further improvement in modeling P in livestock systems such as those presented by Létourneau-Montminy et al. (2010) and Symeou et al. (2014) is expected to improve estimates of the impact of phytase on EP and AP depending on input data availability. Greater use of renewable energy sources in the production of SFI is expected to reduce PED, and it is considered an area where the industry could take action. Animal housing and feed mills were minor contributors in all impact categories, whereas transportation played a role only if long-distance feed imports were involved in the supply chain. Moreover, international trade that exports livestock products may have the effect of increasing "carbon leakage" (Caro et al., 2014b). The sensitivity analysis showed that FCR had an influence in all supplemented scenarios for all impact categories by reducing feed requirement, thereby reducing nutrient excretion. For example, the improved FCR (2.30 instead of 2.75) with the supplementation of SFI reduced GWP by up to 15% compared to unsupplemented alternatives and 12% compared to the fully supplemented alternative in pig production systems. In agreement with our study, da Silva et al. (2014) reported that extensive broiler systems in France contributed to higher environmental impact because of a high (3.10) FCR. In both pig and broiler production systems and all impact categories, a combination of improving FCR and specialty feed supplementation resulted in better outcomes. This study can be used to set benchmarks for sustainable animal production in different regions of the world by providing initial environmental profiles.

Outlook

As mentioned earlier, livestock production has an environmental impact such as GHG emissions, water quality, ocean acidification, and fossil fuel consumption. The demand for livestock products is expected to grow substantially, causing even more environmental pressure. Also, productivity must increase to feed the ever-growing population in a healthy and more sustainable manner because natural resources are being depleted on the planet. Using SFI such as AA or phytase in livestock production can significantly contribute to achieving these goals. Independent of the level of technological development in animal production, the application of SFI may enable feed business operators to reduce resource consumption and environmental impacts at least within the impact categories assessed. Uncertainty in data used to describe the system and in impact calculations can be quantified using methods reported by Mackenzie et al. (2015) for pig systems in Canada. Although in their study only EP was affected by uncertainty in data, the methodology might yield different results in other regions. Although China and other Asian countries are major players in pig and broiler production, the LCA described here did not include the Asia/Pacific region, mainly because of the limited quality and quantity of available data. In addition, the Asia/Pacific region also has a significant contribution from “backyard” production, with even less data available to conduct a rigorous LCA. The authors recommend further work and LCA development in the Asia/Pacific region as more data become available or through primary data collection to assess the global impact of using SFI.

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