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Life cycle assessment of swine production in Brazil: a comparison of four manure management systems

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ABSTRACT

Population growth and the consequent increase in food demand will certainly intensify the threat to the environment. Brazil, the fourth largest producer and exporter of swine meat, has an important role to ensure the fulfillment of the goals of food security and climate change mitigation. Therefore, the aim of this study was to evaluate the environmental impact of swine production in Brazil based on life cycle assessment, comparing four manure management systems: liquid manure storage in slurry tanks; the biodigestor by flare; the biodigestor for energy purposes; and composting. Additionally, we performed a Monte Carlo simulation to evaluate the uncertainty due to different emissions factors to estimate nitrogen-related emissions from the manure-handling stage. The functional unit considered was 1000 kg of swine carcass in the equalization chamber for cutting or further distribution. The results indicated an environmental profile of swine production in Brazil of 3503.29 kg of CO_2 eq. for climate change, 76.13 kg of SO_2 eq. for terrestrial acidification, 2.15 kg of P eq. for freshwater eutrophication, 12.33 kg of N eq. for marine eutrophication, 21,521.12 MJ for cumulative energy demand, 1.63 kg of 1.4-DB eq. for terrestrial ecotoxicity, 1706.26 BDP for biodiversity damage potential and 14.99 m^2 for natural land transformation. Feed production had a significant contribution with a range of 17.6–99.5% for all environmental impact categories. Deforestation represented 9.5 and 31.3% of the total impacts for cumulative energy demand and climate change, respectively. Therefore, avoiding the use of grain from deforested areas can significantly decrease the impacts for these impact categories. Regarding the uncertainty analysis, we observed greater variations for terrestrial acidification in slurry tanks, biodigestor by flare and for energy purposes, while for the case of composting, major uncertainties were observed for climate change. For manure management systems, efforts should be made to reduce the emissions of methane in the storage and ammonia in the field application. In this sense, the comparative life cycle assessment indicated that the biodigestor for energy purposes had the best environmental performance for almost all the environmental impacts, mainly due to the biogas capture and the potential of energy saves. Nevertheless, if the goal is to decrease the impacts for terrestrial acidification and marine eutrophication, the slurry tanks is the most preferable scenario compared to all alternative options.

1. Introduction

The agricultural sector, especially livestock production, has a significant impact on the environment, being responsible for 18% of worldwide carbon dioxide (CO_2) equivalent emissions (de Vries and de Boer, 2010; Steinfeld et al., 2006). In the European Union (EU-27), the consumption of meat and dairy products contributes on average to 24% of the environmental impacts, of which swine meat represents 19–44% (Weidema et al., 2008). Swine production is a recognized pollution source due to the

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large generation of manure and the large consumption of grain for animal feed.

In 2013, the average herd for Brazilian swine production was 38.578 million animals, making Brazil the fourth largest producer and exporter of swine meat in the world (USDA, 2013). In the last decade, production has expanded into the central west region, becoming a potential stage for further environmental impacts (Kunz et al., 2009); however, the state of Santa Catarina (in southern Brazil) is still the major producer in the country, with 19.3% of the national herd (IBGE, 2012). The Environmental Agency of Santa Catarina State (FATMA), through the Normative Instruction no.11/2004, establishes 50 m^3 ha^{-1} $year^{-1}$ as the maximum amount of manure for use in arable land, but depending on the soil requirements for nutrient fertilization, the application rate of manure can be lower (FATMA, 2004).

The most common manure management system (MMS), which is used in 80% of integrated farms, is the storage of manure in open slurry tanks without a natural crust cover, while the biodigestor with flare is used in nearly all of the remaining 20% of farms (Higarashi et al., 2013; Kunz et al., 2005). In both of the MMS, the manure is then applied on land as organic fertilizer. The use of biodigestor has grown in Brazil mainly due to the potential reduction of greenhouse gas (GHG) emissions by the conversion of methane (CH_4) emissions into carbon dioxide in the burning processes (i.e., flares) or into heat or electrical energy (Amon et al., 2006; Cantrell et al., 2008; Massé et al., 2011; Murphy et al., 2004; Oliveira, 2004). Some studies (Amon et al., 2006; Chantigny et al., 2007; Vallejo et al., 2006) have demonstrated that the use of an anaerobic digestion system, such as biodigestor, also reduces nitrous oxide (N_2O) emissions during the manure application compared to the application of raw manure. However, biodigestor does not offer solutions to other manure disposal problems, such as removing N and P or reducing the quantity of manure (Chantigny et al., 2007; Kunz et al., 2009). In this sense, an alternative to open slurry tanks and biodigestor is to handle manure in the solid form by composting.

Life cycle assessment (LCA) is a methodology for the estimation of the potential environmental impacts of products and has been widely used in livestock systems (Reckmann et al., 2012; Thomassen and de Boer, 2005; van der Werf and Petit, 2002). Furthermore, LCA allows the environmental performance evaluation of established scenarios and the ability to compare the improvement options of a process/product throughout its life cycle, such as the manure management system options (Nguyen et al., 2011). Several LCA studies of swine production have been conducted worldwide (Basset-Mens and van der Werf, 2005; Baumgartner et al., 2008; Cederberg and Flysjö, 2004; Dalgaard et al., 2007; Halberg et al., 2007; Kingston et al., 2009; Nguyen et al., 2011; Reckmann et al., 2013; Schenck, 2006; Wiedemann et al., 2010; Williams et al., 2006). Regarding the Brazilian production systems, Spies (2003) conducted a streamlined LCA of swine and poultry production indicating the need for these activities to adjust their management practices to a more sustainable production. In addition, the author notes the need to create a complete LCA from the streamlined LCA to build a more consistent database, also considering the different manure management systems to better understand the environmental effects and the improvements offered by each alternative.

Ruviaro et al. (2012), in a scientific research on LCA application to products worldwide found that specific for Brazilian products, LCA was applied to ethanol, sugarcane, biofuels, agricultural machinery manufacture, coffee, soybeans, orange juice, poultry, aquiculture, and oysters. To date, there is no published paper addressing swine production with a complete LCA for Brazil or other tropical countries, nor is there one that performs a MMS scenario variation with composting and biodigestor by flare. Moreover, there is no uncertainty assessment that encompasses every aspect of these scenarios so that a seamless decision-making process is guaranteed.

Hence, the aim of this study was to evaluate the environmental impacts of swine production in Brazil through the use of a complete LCA, comparing four manure management systems (MMS): liquid manure storage in slurry tanks (Sce.Ref); the biodigestor by flare (Sce.Flare); the biodigestor for energy purposes (Sce.CHP); and composting (Sce.Comp). Additionally, the uncertainty due to different emissions factors was evaluated to estimate the nitrous oxide and ammonia emissions from the manure handling stage.

2. Materials and methods

The environmental impacts were evaluated following ISO standards 14,040 and 14,044 (ISO, 2006a, 2006b), with SimaPro® software. The comprehensive scope of LCA is useful in order to avoid problem-shifting from one phase of the life-cycle to another and it is recognized as a trustworthy, scientific and understandable approach to address the environmental sustainability of human activities (Baitz et al., 2013; Finnveden et al., 2009). On top of that, the use of several mathematical models to address all the environmental aspects to its respective environmental impacts reduces the uncertainty in decision making between different options.

2.1. Goal and scope

The system boundaries of this LCA begin with the crop production, grain drying and processing, piglet production (PP) and growing to finishing (GF) and end at the slaughterhouse with the cooled and eviscerated carcass, as displayed in Fig. 1. The animals are raised in housing with an uneven concrete floor for manure runoff to a downspout that transports the slurry to the manure management system (MMS).

The functional unit (FU) considered was 1000 kg of swine carcass (deadweight) in the equalization chamber for cutting or further distribution.

2.2. Life cycle inventory

The life cycle inventory (LCI) for the animal production and slaughterhouse stage was obtained from the integrated farms of Brazilian agroindustry and represents the southern Brazil. For the other stages, we used data based on the literature.

2.2.1. Crop production

Inputs and emissions data for Brazilian soybean and maize cultivation and processing were obtained from Prudêncio da Silva et al. (2010) and Alvarenga et al. (2012). The data for rice cultivation were obtained from the Ecoinvent® database (Nemecek and Kägi, 2007).

In Brazil, the origin of crop production has an important role in the environmental costs due to the impacts of land transformation (hereinafter: deforestation). Although recent data published by the National Institute for Space Research have indicated that since 2005, the annual rate of deforestation in the Amazon area has decreased (INPE, 2012), this is a major issue for the evaluation of the life cycle in animal production. We assumed impacts from deforestation only for the grains produced in the central west region because in southern Brazil the deforestation occurred many years ago.

To estimate the origin and transport distance of grains, we performed a weighted mean of the amount of grains from the central western and southern regions and the distance to the feed factory located in Santa Catarina, based on the year 2011. Soybean used in swine production in southern Brazil comes mainly from the central west (98%), with 1713 km of distance, while the soybean

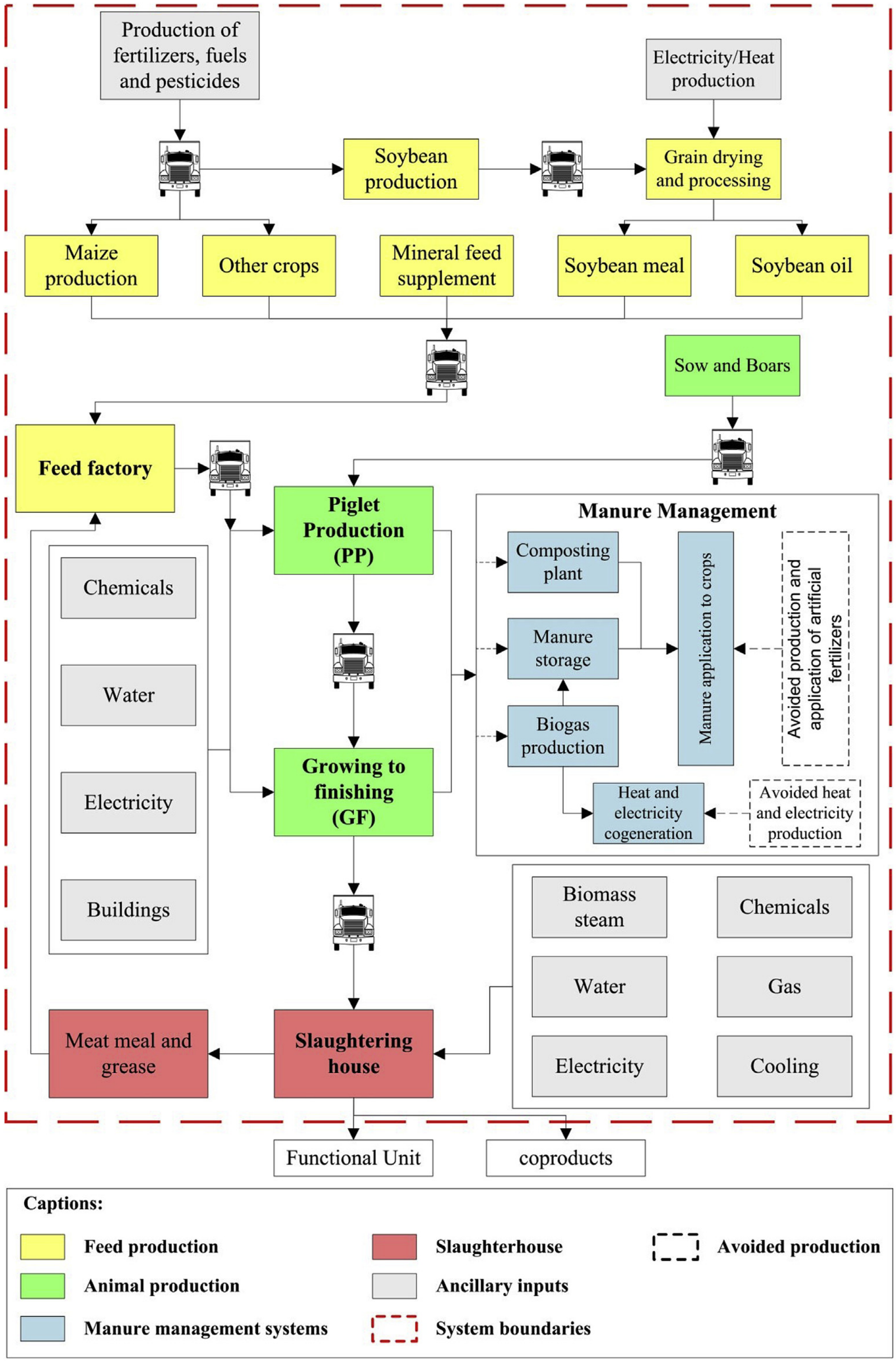

Fig. 1. System boundaries of swine production in southern Brazil.

from the south (2%) is transported over 494 km of distance. Maize grain comes mainly from the southern region (83%), with an average distance of 154 km, whereas from the central west (17%), they are transported over 1559 km.

For deforestation, we considered direct land-use change (dLUC) factors according to (Prudêncio da Silva et al., 2010; Prudêncio da Silva, 2011). This assumption was used for grains (soybeans and maize) produced in the central west region.

2.2.2. Feed composition

In Brazil, swine feed composition uses mainly soybean meal as the protein source and maize as the energy source. Due to confidentiality, we divided the feed formulations into three main types (sows, piglets and growing to finishing), based on a weighted mean of the feed intake for each step of animal breeding and the amount of each ingredient, as displayed in Table 1.

Table 1
Animal feed composition and feed consumption.

Ingredients	Sows		Piglets		Swine	
Feed consumption	kg FU^{-1}	%	kg FU^{-1}	%	kg FU^{-1}	%
Maize	25.30	60.23	14.97	55.02	169.31	66.67
Soybean meal	9.52	22.66	6.04	22.20	70.72	27.85
Soybean oil	–	–	–	–	0.84	0.33
Soybean hulls	2.70	6.42	–	–	–	–
Maize gluten meal	–	–	0.82	3.00	–	–
$Ca(HPO_4)$	0.42	0.99	0.12	0.45	0.89	0.35
NaCl	0.21	0.49	0.07	0.26	1.32	0.52
Limestone	0.49	1.17	0.16	0.58	2.44	0.96
L-Lysine HCl	0.06	0.14	0.09	0.33	0.13	0.05
Dl-Methionine	–	–	0.01	0.03	0.05	0.02
Rice bran meal	2.20	5.24	–	–	3.20	1.26
Premix	0.13	0.30	1.95	7.17	0.69	0.27
Animal fat	0.89	2.12	0.93	3.43	1.14	0.45
Animal meal	–	–	0.89	3.28	3.20	1.26
Other amino acids	0.01	0.03	0.03	0.10	0.03	0.01
Other ingredients[a]	0.09	0.21	1.13	4.15	–	–
Total	42.00	100.00	27.20	100.00	253.96	100.00

[a] Mycotoxin binders, flavors and sweetener agent.

2.2.3. Animal production

For the piglet production and growing to finishing stages, the technical performance indicators based on the agroindustry are displayed in Table 2.

The overall amount of manure in the piglet production stage was estimated according to Oliveira (1993). In the growing to finishing stage, we adopted the values described by Tavares et al. (2014a). For housing emissions in animal production, we estimated the data according to IPCC (2006) and Hutchings et al. (2013). For enteric emissions, we use Tier 1 assuming 1.5 kg CH_4 swine^{-1} year^{-1} (IPCC, 2006). Table A1 (Supplementary materials) summarizes the main inputs and outputs for animal production.

2.2.4. Manure management systems (MMS)

Manure composition for both the piglet production and growing to finishing stages was based on (Tavares et al., 2014b). The CO_2 and CH_4 emissions during manure storage were estimated according to Hamelin et al. (2010, 2011) and the IPCC (2006), respectively. The N-related emissions during storage and for field application were estimated considering Dämmgen and Hutchings (2008), IPCC (2006), Hutchings et al. (2013) and Nemecek and Kägi (2007); see supplementary materials (Table A2).

The baseline scenario (Sce.Ref) considers the manure management system with open slurry tanks without a natural crust cover and with a revetment of high-density polyethylene (HDPE) and a storage time of 120 days, which according to the agroindustry represents approximately 80% of the integrated farms.

For biodigestor with flare (Sce.Flare) and biodigestor for energy purposes (Sce.CHP), manure is stored for 40 days in a digester and then for 80 days in open slurry tanks. We considered a concrete digester with a revetment of polyvinylchloride (PVC). In Sce.Flare, emissions from the flare were estimated according to Hamelin et al. (2010) and UNFCCC (2012) considering a flare efficiency of 90%. In Sce.CHP, the biogas production as well as the electricity and heat avoided were estimated according to Hamelin et al. (2010, 2011), thus resulting in a positive impact for this scenario. In the manure management system by composting (Sce.Comp), sawdust was used as a substrate with a manure application rate of 10 L kg^{-1} and a storage time of 135 days. Manure was handled in a facility with low walls and concrete floors and a roof of transparent PVC (Oliveira and Higarashi, 2006a). For detailed information of the emissions for the manure management system, see Table A2 (Supplementary materials).

2.2.5. Slaughterhouse

After the on-farm stage, the finished swine were transported to the slaughterhouse. Dead animals and those injured in transportation were sent to the meat meal and grease factory (FFG). The remaining were sent through the processes of bleeding, scalding, dehairing and toilette, head removal, evisceration, carcass splitting and inspection. Data for the slaughterhouse stage were collected from the agroindustry and represent a facility with modern technology (Table A4, Supplementary materials).

2.3. Allocation procedures

For grain processing, we used economic allocation. For the piglet production stage, we used mass allocation for the sows and boars sent to slaughter (i.e., piglets: 82.66%; sows: 16.86%; boars: 0.48%). For the manure applied in soil (all scenarios) and the electricity and heat in Sce.CHP, we use the substitution method concept; i.e. the use of manure as organic fertilizer avoids the production of chemical fertilizer (Basset-Mens and van der Werf, 2005; Dalgaard et al., 2007; Kingston et al., 2009; Kool et al., 2009; Nguyen et al., 2011; Williams et al., 2006), and the use of the biogas generated in Sce.CHP avoids electricity consumption from the Brazilian grid (Frischknecht et al., 2007) and the wood-based heat (Bauer, 2007) used in chicken production (Oliveira and Higarashi, 2006b).

For coproducts in the slaughterhouse, we used the mass allocation procedure. However, for condemned carcasses and inedible offal (i.e., residues) the environmental burdens were attributed to the swine carcass (carcass: 86.9%; edible offal and other coproducts: 13.1%).

2.4. Life cycle impact assessment (LCIA)

We choose a problem-oriented method for the impact assessment, the ReCiPe (H) v.1.08 (Goedkoop et al., 2009). The environmental impact categories evaluated were as follows: (i) climate change; (ii) terrestrial acidification; (iii) freshwater eutrophication; (iv) marine eutrophication; (v) terrestrial ecotoxicity; and (vi) natural land transformation. We also evaluated the total cumulative energy demand version 1.08 (PRé Consultants, 2013) and biodiversity damage potential from the de Baan et al. (2013) method expressed in BDP, with site-specific characterization factors for arable land and site-generic characterization for other land types. Regarding Brazilian biome distribution, we used the data from the Conservation and Sustainable Use of Brazilian Biological Diversity Project (MMA, 2007). The distribution for the central west is as

Table 2
Technical performance indicators of a vertically integrated system of production for swine in southern Brazil.

Piglet production (PP)		Growing to finishing (GF)	
Weaned piglet per sow per year	25 piglet sow^{-1} year^{-1}	Mortality	2.5%
Feed per sow (boar included)	1050 kg year^{-1}	Feed conversion rate	2.51 kg
Gestation sows	114 days	Slaughter age	171 days
Dry sow	7 days	Slaughter weight	125 kg
Lactating sows	21 days	Carcass yield	73.9%
Productive life	2.5 years		
Sow replacement	37.5%		
Sow liveweight for slaughtering	220 kg		
Weaning mortality	1.4%		
Feed conversion rate	1.54 kg		
Weaning age	38 days		
Exit liveweight	23.7 kg		

follows: 34.0% tropical forest biome and 66.0% savannah; for the south: 99.3% tropical forest and 0.7% savannah biome.

Additionally for comparison purposes and for a better understanding of the impact magnitude on eutrophication, we evaluated the eutrophication potential from CML-IA method (Guinée et al., 2002). We choose this method because it was used in the most of the studies in the literature.

2.5. Uncertainty analysis

In the manure management system scenarios, the N-related emissions were estimated with the model developed by Hutchings et al. (2013) with some modifications to calculate the flows of nitrogen. This model uses input parameters, such as emission factors (EF), which represent the proportion of the N in manure that is emitted as NH_3, N_2O, N_2, NO_x and NO_3. When data were available, we used the EF for the Brazilian scenario; nevertheless, when no data were available, we used the European EF. However, the adoption of EF from other scenarios brings uncertainty to the results, which can have a significant influence on the comparative scenarios. To estimate the uncertainty of the input parameters, we performed a survey of the available EFs (Supplementary materials Tables A5, A6, A7, A8 and A9) and established minimum and maximum values for a Monte Carlo (MC) simulation, assuming a uniform distribution. The Monte Carlo simulation was performed with SimaPro® (version 8.0.2), which allows for uncertainty propagation over all of the parameters with 10,000 independent simulations. We used a 95% confidence interval.

3. Results

3.1. LCA of swine from southern Brazil

The results per ton of swine carcass (deadweight) exhibited a significant contribution from feed production (a range of 17.6–99.5%) for all of the environmental impact categories and was a bottleneck for climate change, terrestrial acidification, marine eutrophication, biodiversity damage potential, natural land transformation, and cumulative energy demand (Table 3). On the other hand, the manure management system (MMS) contributed as high as 59.7% and 78.6% of the total impact for freshwater eutrophication and terrestrial ecotoxicity, respectively.

The CO_2 was mainly responsible for the impacts on climate change with 63.1% of total emissions, of which the CO_2 emissions from land-use change (dLUC) contributed to 32.0%. CH_4 emissions accounted for 18.5%, and the majority of it was due to manure storage. The other 18.3% contributing to climate change were from N_2O emissions, much of which was from the field emissions from maize production due to the use of urea as N fertilizer; the manure application as organic fertilizer also made a significant contribution to N_2O emissions.

Analyzing the life cycle stages, feed production in the growing to finishing and piglet production was responsible for 61.5% and 13.5% of total climate change, respectively. The majority of the climate change from soybean crops was due to the Amazon biome deforestation from the central west grains.

The MMS system was the second main contributor to the climate change impacts, with 17.7% of total emissions. Emissions due to enteric fermentation in animal housing for the growing to finishing and piglet production were 96.7 and 31.4 kg of CO_2 eq. per ton of swine carcass, respectively.

Ammonia emissions represented the primary contribution for the terrestrial acidification (91.8%), followed by the nitrogen oxide and sulfur dioxide emissions. Field emissions from maize crops (used as feed) were also the main source of the impacts on this category, with 55.1% of total NH_3 emissions. Manure storage and application in soil emitted 19.7%, while 18.3% of the NH_3 was from animal housing.

For freshwater eutrophication, the manure application as organic fertilizer was the most significant (61.7%), mainly due to the potential for P leaching. Soybean meal was responsible for 21.4% of the impacts on freshwater eutrophication, while the emissions from maize cultivation contributed with 15.8%.

Marine eutrophication was caused by nitrate (76.3%) followed by ammonia (21.3%). Grain production was responsible for the emission of 96.0% and 59.3% of the total nitrate and ammonia, respectively.

Production of feed was also the main source of the intensive use of energy. Greater energy demand in crop cultivation resulted from artificial fertilizer production (25.0%), grain transportation (26.0%) and deforestation (9.5%).

Terrestrial ecotoxicity was mainly caused by the manure application to soil, due to copper and zinc emissions (61.5% and 19.9%, respectively).

For biodiversity damage potential maize crops were the main source of the biodiversity damage (49.0%), while soybean meal accounted for 45.8%. Maize is used in larger amounts in the feed composition. However, because the majority of the soybean meal came from the central west region, an area that constitutes 66% of the savannah biome (see item 2.2.1. and 2.4.), soybean meal made a significant contribution to this category (the savannah has a higher characterization factor than the tropical forest – see de Baan et al., 2013).

Table 3
Environmental impacts per ton of swine carcass produced in South Brazil.

Life cycle stages	Impact categories							
	Climate change	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Cumulative energy demand	Terrestrial ecotoxicity	Biodiversity damage potential	Natural land transformation
	kg CO_2 eq.	kg SO_2 eq.	kg P eq.	kg N eq.	MJ	kg 1.4-DCB eq.	BDP	m^2
Feed for piglet production[a]	498.2	8.852	0.161	1.938	4127.8	0.060	302.6	2.440
Piglet production[b]	142.6	3.598	0.168	0.182	692.20	0.180	1.535	0.026
Feed for growing to finishing	2268	39.24	0.720	8.933	17,217	0.235	1401	12.48
Growing to finishing[b]	727.7	25.85	1.175	1.313	1231.3	1.181	5.622	0.029
Slaughtering	48.86	0.084	0.008	0.011	1222.5	0.025	2.118	0.056
Sub-total	3685	77.62	2.232	12.38	24,491	1.681	1713	15.04
Avoided fertilizer	−182.0	−1.485	−0.084	−0.049	−2969.5	−0.053	−6.369	−0.049
Total	3503	76.13	2.148	12.33	21,521	1.629	1706	14.99

[a] Including feed for sows.
[b] Including housing, storage and spreading emissions.

Soybean meal production made a major contribution to natural land transformation (83.5%), because we assumed that the impacts of deforestation for grain production in Brazil must be considered only in the central western region (Prudêncio da Silva et al., 2010; Prudêncio da Silva, 2011).

3.2. Impacts of different manure management systems

The comparative LCA indicated that the Sce.Comp has the worst environmental performance for nearly all environmental impacts, except for marine eutrophication, in which Sce.Flare had the highest N eq. emissions (Table 4).

For climate change, Sce.CHP has the lowest CO_2 eq. emissions per ton of swine carcass followed by Sce.Flare and Sce.Ref. The comparison with the baseline scenario for this impact category (i.e., Sce.Ref) indicated that Sce.Flare could reduce 3.3% of CO_2 eq. (114.5 kg) per functional unit due to methane conversion into CO_2 by biogas flaring. For Sce.CHP, due to the potential for biogas usage for electricity and heat production, it was possible to reduce by 11.1% the impacts (389.4 kg CO_2 eq.). Sce.Comp had approximately the same GHG emissions of the Sce.Ref with 3552 kg CO_2 eq.

Although Sce.Flare and Sce.CHP exhibited high NH_3 emissions (see Table A2, Supplementary materials), Sce.Comp resulted in slightly higher SO_2 eq. emissions compared to others scenarios due to the emissions of nitrogen oxide in the composting process.

For marine eutrophication, the results were very similar for all scenarios. The slightly higher emissions in scenarios Sce.Flare and Sce.CHP were due to the ammonia emissions in the slurry tank post biodigestor storage. Ammonia emissions were estimated according to the content of total ammonia nitrogen (TAN) in the manure (see supplementary material). The proportion of N-organic mineralized in the biodigestor (Hutchings et al., 2013) is higher than in the slurry tank (Sce.Ref) and in the composting process (Sce.Comp), which results in a higher content of TAN entering the slurry tank post biodigestor storage, thus causing greater ammonia emissions. The high content of TAN occurred due to the reduction in the manure carbon and dry matter, which led to an enhanced potential for NH_3 emissions (Amon et al., 2006).

The differences in the cumulative energy demand were due to the avoided products. For Sce.Ref, Sce.Flare and Sce.Comp, the results were driven by the amount of avoided fertilizer production, while for Sce.CHP, the positive impacts from the avoided energy and heat production can be added. The agronomic value of the organic fertilizer in Sce.Flare, Sce.CHP and Sce.Comp is higher than in the Sce.Ref due to the amount of N directly available for the crops. However, in Sce.Comp, the avoided fertilizer is lower because greater N loss occurs in the manure storage when compared to other manure management systems.

For biodiversity damage potential and natural land transformation, the Sce.Comp was the worst scenario, although minor differences were observed. For both impact categories, the use of sawdust as a substrate in the composting process was responsible for the differences between Sce.Comp and the other scenarios. For freshwater eutrophication and terrestrial ecotoxicity, the results were very similar for all scenarios. Minor differences in the results were due to the agronomic value estimated for the manure applied as organic fertilizer.

3.3. Uncertainties in the N-related emissions in the manure management system comparison

Table 5 summarizes the results of the Monte Carlo simulation for the impact categories that are most affected by the N-related emissions in the manure management systems. Major uncertainties were observed for terrestrial acidification in all scenarios with a coefficient of variation (CV) up to 6.8%. For climate change due to N_2O emissions, major uncertainties were observed for the Sce.Comp followed by the Sce.Ref. For marine eutrophication the coefficient of variation were around 1%, the low uncertainty for this impact category was due to the minor variations in nitrate emissions. Nitrate emissions are the main driver for the impacts on marine eutrophication. While for the remaining impact categories, we observed minor variations with the CV less than 0.9% for all scenarios. The very low uncertainty for biodiversity damage potential, cumulative energy demand, freshwater eutrophication, natural land transformation and terrestrial ecotoxicity were due to the amount of N fertilizer avoided, because these impact categories are not affected by the (direct) N-related emissions, i.e., more N loss in the manure management system results in minor amount of N available for application in the soil and, as consequence, less urea fertilizer avoided.

Regarding the emissions, NO_x exhibited the highest uncertainty with a CV of 39.6–48.9%, which partly explains the high uncertainty for terrestrial acidification in Sce.Ref, Sce.Flare and Sce.CHP. The second most uncertain emission was N_2O for Sce.Ref and Sce.Comp, with a CV of 33.2% and 32.5%, respectively; meanwhile, N_2 emissions were the second most uncertain emission for Sce.Flare and Sce.CHP, with CVs of 25.5% and 25.3%, respectively. The highest uncertainties for ammonia and nitrate emissions were observed in Sce.Ref, with a CV of 17.1% and 10.4%, respectively.

Comparing the alternative manure management system scenarios with the baseline scenario (Sce.Ref) through the Monte Carlo simulation, it is possible to state that Sce.CHP in 100% of the cases will be favorable for climate change, freshwater eutrophication, cumulative energy demand, terrestrial ecotoxicity, biodiversity damage potential and natural land transformation (Table 6), while for terrestrial acidification and marine eutrophication, this scenario will only exhibit lower emissions in 20.6% and 25.4% of the cases, respectively. The climate change for the Sce.Flare scenario will be favorable in 95% of the cases compared to Sce.Ref, while for the other impact categories, the Monte Carlo simulation indicated that this alternative had no significant effect as displayed in Table 6. For the Sce.Comp, the Monte Carlo results indicated that this scenario will be preferable for climate change in 51.7% of the cases compared to Sce.Ref; for freshwater eutrophication, cumulative energy demand, terrestrial ecotoxicity, biodiversity damage potential and

Table 4
Environmental profile for the four MMS scenarios. (Differences between the scenarios are given in percentages of the baseline scenario, i.e., Sce.Ref).

	Climate change		Terrestrial acidification		Freshwater eutrophication		Marine eutrophication		Cumulative energy demand		Terrestrial ecotoxicity		Biodiversity damage potential		Natural land transformation	
	kg CO_2 eq.	% of Sce.Ref	kg SO_2 eq.	% of Sce.Ref	kg P eq.	% of Sce.Ref	kg N eq.	% of Sce.Ref	MJ	% of Sce.Ref	kg 1.4-DB eq.	% of Sce.Ref	BDP	% of Sce.Ref	m^2	% of Sce.Ref
Sce.Ref	3503		76.14		2.148		12.33		21,521		1.629		1706		14.99	
Sce.Flare	3389	96.7	82.43	108.3	2.147	100.0	12.50	101.4	21,472	99.8	1.631	100.2	1706	100.0	14.99	100.0
Sce.CHP	3114	88.9	82.38	108.2	2.131	99.2	12.49	101.3	20,027	93.1	1.572	96.6	1696	99.4	14.94	99.7
Sce.Comp	3552	101.4	82.73	108.7	2.161	100.6	12.42	100.8	22,585	104.9	1.642	100.8	1890	110.8	15.12	100.9

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Table 5
Results of the Monte Carlo simulation for the impact categories direct affected by the N-related emissions.

	Climate change kg CO_2 eq.			Terrestrial acidification kg SO_2 eq.			Marine eutrophication kg N eq.		
	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV
Sce.Ref	3610	3450–3770	2.4%	78.9	68.0–88.0	6.8%	12.4	12.1–12.7	1.3%
Sce.Flare	3450	3380–3530	1.3%	84.3	77.9–90.4	4.1%	12.6	12.4–12.7	0.9%
Sce.CHP	3180	3100–3260	1.4%	84.3	77.9–90.3	4.1%	12.5	12.3–12.7	0.9%
Sce.Comp	3600	3270–3970	5.6%	84.8	78.3–90.8	4.0%	12.5	12.3–12.7	0.9%

natural land transformation, Sce.Comp in 100% of the cases will have high emissions compared to Sce.Ref.

4. Discussion

Comparing our results with the literature (Table 7), we had higher emissions for climate change than those for (GAP in Basset-Mens and van der Werf, 2005; Dalgaard et al., 2007; Halberg et al., 2007; Nguyen et al., 2011; Reckmann et al., 2013; Spies, 2003; and the Southern production in Wiedemann et al., 2010). The main reason for the high CO_2 eq. emissions in our study seems to be the inclusion of the deforestation impacts (i.e., dLUC) in grain production. Only the deforestation represented 31.3% of the impacts in our system for climate change. In this sense, Brazilian government and industry have made efforts to identify soybean produced in deforested areas from Amazon Biome, with initiatives such as the Soy Moratorium as a pledge to not commercialize soybean produced in those areas after 2006 (Prudêncio da Silva, 2011). Recent data indicated that from cleared areas in Amazon biome during the Soy Moratorium (2006–2012) less than 0.77% was used for soybean production (ABIOVE, 2013), which are lower than those described by Prudêncio da Silva et al. (2010), and used in this study.

The high impacts on climate change in the Swedish production (Cederberg and Flysjö, 2004), compared to our study, may be due to the longer period of animal feeding and the animal final weight (160 kg). The final weight contributes to increased impacts because the daily weight gain generally decreases according to the animal age. A low feed conversion rate is also one of the reasons for the high impacts on climate change in Kingston et al. (2009), Schenck (2006), Williams et al. (2006), Spanish production in Baumgartner et al. (2008), and the organic scenarios in Kool et al. (2009) compared to our study. In addition, the method of calculation of nitrous oxide and ammonia emissions can also explain the highest impacts on climate change, terrestrial acidification and eutrophication potential for certain studies (Kingston et al., 2009; Williams et al., 2006).

For eutrophication potential, our study had better results than (Cederberg and Flysjö, 2004; Halberg et al., 2007; Kingston et al., 2009; Schenck, 2006; Spies, 2003; Williams et al., 2006) and similar results to (Basset-Mens and van der Werf, 2005; Dalgaard et al., 2007; Nguyen et al., 2011; Reckmann et al., 2013). The main differences for eutrophication potential and terrestrial acidification compared to (Kingston et al., 2009; Spies, 2003; Williams et al., 2006) were due to the high estimation of ammonia emissions on these studies.

The lower values for terrestrial acidification in the red label scenario (Basset-Mens and van der Werf, 2005) seem to be a consequence of solid manure in the crop cultivation, which results in a large decrease in the ammonia losses during manure application.

The terrestrial ecotoxicity was evaluated only in Basset-Mens and van der Werf (2005) and Baumgartner et al. (2008); however, due to differences in the models and characterization factors in the LCIA, the results are not comparable. This was also why we did not compare the results for the cumulative energy demand. Regarding the other impact categories, we could not find other studies that have evaluated freshwater eutrophication, marine eutrophication, natural land transformation and biodiversity damage potential.

Analyzing the breakdown of the emissions contribution per impact category, our results differ from the LCA studies for climate change. The biggest contributor for the climate change in Brazilian swine production was the CO_2 emissions, followed by CH_4 and N_2O; in some European studies (Cederberg and Flysjö, 2004; Dalgaard et al., 2007; Reckmann et al., 2013) the contribution of N_2O is much higher. CO_2 and CH_4 are secondary emissions with almost the same share of the contribution for climate change. The greater amount of CO_2 emitted in the Brazilian system is strongly related to the impact of deforestation.

For the terrestrial acidification, our results were in line with the other LCA studies (Basset-Mens and van der Werf, 2005; Cederberg and Flysjö, 2004; Dalgaard et al., 2007; Kingston et al., 2009; Reckmann et al., 2013; Spies, 2003; Williams et al., 2006), with NH_3 emissions as the main driver for this impact category. With respect to eutrophication potential (the CML-IA method), our results were similar to Reckmann et al. (2013), with NH_3 as the main contributor to this impact category (44.3%), and different from (Basset-Mens and van der Werf, 2005; Baumgartner et al., 2008; Cederberg and Flysjö, 2004; Dalgaard et al., 2007), in which NO_3 emissions represented the greatest contribution to eutrophication potential (56.1–78.0%).

Regarding the manure management systems used by the Brazilian swine producers, the use of biodigestor seems to be the most favorable alternative, especially if the captured biogas is used for energy purposes. An additional advantage of the biodigestor scenarios is the agronomic value of the manure due to the higher mineralized N content. According to some studies (Amon et al., 2006; Chantigny et al., 2007) the reduction of the dry matter content increases the infiltration rate of the manure into the soil and thereby reduces the NH_3 emissions after manure application. However, in our estimation the high content of total ammonia nitrogen resulted in the high potential for NH_3 emissions generating a greater terrestrial acidification for Sce.Flare, Sce.CHP and Sce.Comp (see Table 4), which highlights the importance of the need to better understand the N-related emissions.

With respect to uncertainties in LCA modeling, besides the differences in the scope definition, the greater uncertainties came in

Table 6
Probability of the alternatives for manure management systems indicating lower impacts than those for the Sce.Ref (in %).

Comparison		Climate change	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Cumulative energy demand	Terrestrial ecotoxicity	Biodiversity damage potential	Natural land transformation
Sce.Ref	≥Sce.Flare	95.0	20.4	38.1	24.6	44.1	4.1	16.3	0.6
	≥Sce.CHP	100.0	20.6	100.0	25.4	100.0	100.0	100.0	100.0
	≥Sce.Comp	51.7	18.8	0.0	34.0	0.0	0.0	0.0	0.0

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Table 7
LCA results for swine production worldwide (Results per ton of swine carcass).

Author	Country[a]	System	Climate change (kg CO_2 eq.)	Eutrophication potential (kg PO_4^{3-} eq.)	Terrestrial acidification (kg SO_2 eq.)	Cumulative energy demand (MJ)
Our study	BR	Intensive production	3503	22.54[b]	76.13	21,521
Spies (2003)	BR[c]	Intensive production	2022	112.29	232.80	9559
Cederberg; Flysjö (2004)	SE	Animal welfare	4080	24.78	51.94	16,090
		Environmental care	3630	15.87	26.13	14,700
		Product quality and price	4430	28.04	64.19	18,430
Basset-Mens and van der Werf (2005)	FR[c]	Good Agricultural Practice (GAP)	2704	24.46	51.15	18,695
		Red Label (RL)	4068	19.52	26.57	21,046
		Organic (OA)	4668	25.34	43.74	26,102
Williams et al. (2006)	UK	Non-organic	6360	100.00	395.00	16,700
		Organic	5640	57.00	129.00	14,500
Schenck (2006)	US	Intensive	9400	60.00	150.00	–
		Environmental care	3800	65.00	100.00	–
Dalgaard et al. (2007)	DK	Conventional	3300	23.20	45.00	–
	UK	Conventional	3400	30.10	64.00	–
	NL[d]	Conventional	3600	21.90	42.00	–
Halberg et al. (2007)	DK[c]	Organic (free-range sows)	3433	31.63	67.37	–
		Organic (all free-range)	3904	44.80	72.19	–
		Organic (tent)	3327	31.75	59.85	–
Hirschfeld et al. (2008)	DE[c]	–	3645	–	–	–
Baumgartner et al. (2008)	DE[c]	Fully slatted	3527	19.75	45.03	31,864
	ES[c]	Fully slatted	4527	36.20	75.96	39,506
Kingston et al. (2009)	UK	Indoor (slatted flooring)	4800	42.50	138.00	–
		Indoor (loose bedding)	5700	78.00	289.00	–
		Outdoor bred (loose bedding)	5700	71.50	249.00	–
		Indoor (slatted flooring)	4400	42.00	141.00	–
		Indoor (slatted flooring, anaerobic digestion)	4100	34.90	121.00	–
		Organic (outdoor, loose bedding)	5400	66.00	199.00	–
Kool et al. (2009)	NL	Conventional	3600	–	–	–
		Organic	4300	–	–	–
	UK	Conventional	3500	–	–	–
		Organic	4400	–	–	–
	DE	Conventional	3700	–	–	–
		Organic	5000	–	–	–
	DK	Conventional	3500	–	–	–
		Organic	4000	–	–	–
Wiedemann et al. (2010)	AU	Conventional (northern)	5500	–	–	24,500
		Conventional (southern)	3100	–	–	20,300
Nguyen et al. (2011)	DK	Conventional	3100	24.30	56.00	21,000
		Conventional[e]	3400	32.10	61.00	22,000
Reckmann et al. (2013)	DE	Standard	3220	23.30	57.10	19,500

[a] Country: BR – Brazil; SE – Sweden; FR – France; UK – United Kingdom; US – United States; DK – Denmark; NL – Netherlands; DE – Deutschland; ES – Spain; AU – Australia.
[b] Eutrophication potential (EP) from CML-IA method (Guinée et al., 2002).
[c] Results estimated per ton of carcass with a carcass yield of 73.9% and the same allocation of our study to the byproducts in the slaughtering stage.
[d] Including transport to the Port of Harwich.
[e] Consequential LCA.

general from the estimation of CH_4, N_2O and NH_3 emissions in crop cultivation, animal rearing and in the manure management system. This uncertainty is present because the emissions are not known and are very difficult to measure because of economic costs and the long measurement periods in the field. As previously stated by Rigolot et al. (2010), there is a need for improvement in the databases and emissions measurement reports.

5. Conclusions

The LCA helped to identify feed production as the main source for the environmental impacts of the analyzed system, so the feed conversion rate is a key determinant for decreasing the impacts of the swine supply chain. Regarding the options to decrease the emissions in the manure management system, Sce.CHP seems to be the most suitable alternative for climate change, freshwater eutrophication, cumulative energy demand, terrestrial ecotoxicity, biodiversity damage potential and natural land transformation, compared to the Sce.Ref. Nevertheless, if the goal is to decrease the impacts for terrestrial acidification and marine eutrophication, the Sce.Ref is the most preferable scenario compared to all of the alternative options. The use of composting as an alternative to open slurry tanks should be used only if N_2O emissions can be reduced once an increase of this emission is observed.

With respect to N-related emissions, the Monte Carlo simulation indicated great uncertainties for the N_2O emissions and consequently the NO_x emissions because we assume nitrogen oxides to be three times as large as the direct N_2O emission. Therefore, more studies should be developed to decrease the variability of N_2O emissions from the manure handling.

As a further recommendation, we suggest conducting an LCA for swine production in the central western region of Brazil because lower grain transportation distances can help decrease the use of fossil fuels and emissions with the potential to cause climate change and cumulative energy demand. There is also a need to create specific emissions factors for swine production in Brazil because the emissions related to housing, storage and the field exhibit a significant contribution for almost all of the impacts.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.10.035.

References

ABIOVE, 2013. Moratória da Soja: Mapeamento e monitoramento do plantio de soja no bioma Amazônia – 6° Ano. (Soy Moratorium) [online] Available from: http://www.abiove.org.br/site/_FILES/Portugues/03022014-160810-port_final_baixa.pdf.

Alvarenga, R.A.F., Prudêncio da Silva, V., Soares, S.R., 2012. Comparison of the ecological footprint and a life cycle impact assessment method for a case study on Brazilian broiler feed production. J. Clean. Prod. 28, 25–32. http://dx.doi.org/10.1016/j.jclepro.2011.06.023.

Amon, B., Kryvoruchko, V., Amon, T., Zechmeister-Boltenstern, S., 2006. Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agric. Ecosyst. Environ. 112, 153–162. http://dx.doi.org/10.1016/j.agee.2005.08.030.

Baitz, M., Albrecht, S., Brauner, E., Broadbent, C., Castellan, G., Conrath, P., Fava, J., Finkbeiner, M., Fischer, M., Fullana I Palmer, P., Krinke, S., Leroy, C., Loebel, O., Mckeown, P., Mersiowsky, I., Möginger, B., Pfaadt, M., Rebitzer, G., Rother, E., Ruhland, K., Schanssema, A., Tikana, L., 2013. LCA's theory and practice: like ebony and ivory living in perfect harmony? Int. J. Life Cycle Assess. 18, 5–13. http://dx.doi.org/10.1007/s11367-012-0476-x.

Basset-Mens, C., van der Werf, H.M.G., 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. Agric. Ecosyst. Environ. 105, 127–144. http://dx.doi.org/10.1016/j.agee.2004.05.007.

Bauer, C., 2007. Holzenergie. In: Dones, R., et al. (Eds.), Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH. Final report Ecoinvent no. 6-IX.

Baumgartner, D.U., de Baan, L., Nemecek, T., 2008. European grain legumes — environment-friendly animal feed? Life cycle assessment of pork, chicken meat, egg and milk production. In: Federal Department of Economic Affairs DEA. Agroscope Reckenholz-Tänikon Research Station ART, Zürich, Zwitzerland [online] Available from: http://www.agroscope.admin.ch/oekobilanzen/01199/06392/index.html?lang=de&download=NHzLpZeg7t,lnp6I0NTU042l2Z6ln1acy4Zn4Z2qZpnO2Yuq2Z6gpJCEe4J,fmym162epYbg2c_JjKbNoKSn6A–.

Cantrell, K.B., Ducey, T., Ro, K.S., Hunt, P.G., 2008. Livestock waste-to-bioenergy generation opportunities. Bioresour. Technol. 99, 7941–7953. http://dx.doi.org/10.1016/j.biortech.2008.02.061.

Chantigny, M.H., Angers, D.A., Rochette, P., Belanger, G., Massé, D.I., Côté, D., 2007. Gaseous nitrogen emissions and forage nitrogen uptake on soils fertilized with raw and treated swine manure. J. Environ. Qual. 36, 1864–1872. http://dx.doi.org/10.2134/jeq2007.0083.

Cederberg, C., Flysjö, A., 2004. Environmental Assessment of Future Pig Farming Systems: Quantifications of Three Scenarios from the FOOD 21 Synthesis Work. Rapport n° 733. The Swedish Institute for Food and Biotechnology – SIK [online] Available from: http://www.vaxteko.nu/html/sll/institutet_livsm_bioteknik/sik-rapport/SIK723/SIK723.PDF.

Dalgaard, R., Halberg, N., Hermansen, J.E., 2007. Danish Pork Production: an Environmental Assessment. In: DJF Animal Science, vol. 82, p. 34 [online] Available from: http://www.lcafood.dk/djfhus82ny.pdf.

Dämmgen, U., Hutchings, N.J., 2008. Emissions of gaseous nitrogen species from manure management: a new approach. Environ. Pollut. 154, 488–497. http://dx.doi.org/10.1016/j.envpol.2007.03.017.

de Baan, L., Alkemade, R., Koellner, T., 2013. Land use impacts on biodiversity in LCA: a global approach. Int. J. Life Cycle Assess. 18, 1216–1230. http://dx.doi.org/10.1007/s11367-012-0412-0.

de Vries, M., de Boer, I.J.M., 2010. Comparing environmental impacts for livestock products: a review of life cycle assessments. Livest. Sci. 128, 1–11. http://dx.doi.org/10.1016/j.livsci.2009.11.007.

FATMA, 2004. Instrução Normativa IN-11. Portaria Intersetorial n°01/04, de 24.03.2004. FATMA, Florianópolis [online] Available from: http://www.fatma.sc.gov.br/conteudo/instrucoes-normativas.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manage. 91, 1–21. http://dx.doi.org/10.1016/j.jenvman.2009.06.018.

Frischknecht, R., Tuchschmid, M., Faist-Emmenegger, M., Bauer, C., Dones, R., 2007. Strommix und Stromnetz. Ecoinvent report n°6, v2.0. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland.

Goedkoop, M.J., Heijungs, R., Huijbregts, M., de Schryver, A., Struijs, J., van Zelm, R., 2009. ReCiPe 2008: a Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. Report 1: Characterisation. Ministry of Housing Spatial Planning and the Environment, The Hague, The Netherlands [online] Available from: http://www.pre-sustainability.com/download/misc/ReCiPe_main_report_final_27-02-2009_web.pdf.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J., 2002. Life Cycle Assessment. An Operational Guide to the ISO Standards. Centre of Environmental Science, Leiden University, Leiden, The Netherlands.

Halberg, N., Hermansen, J., Kristensen, I.S., Eriksen, J., Tvedegaard, N., 2007. Comparative environmental assessment of three systems for organic production in Denmark. In: Proceedings Organic Agriculture in Asia 2008, pp. 249–261 [online] Available from: http://orgprints.org/15585/1/15585.pdf.

Hamelin, L., Wesnæs, M., Wenzel, H., 2010. Life Cycle Assessment of Biogas from Separated Slurry. Environmental project no. 1329. Faculty of Agricultural Sciences, Aarhus University [online] Available from: http://www2.mst.dk/udgiv/publications/2010/978-87-92668-03-5/pdf/978-87-92668-04-2.pdf.

Hamelin, L., Wesnaes, M., Wenzel, H., Petersen, B.M., 2011. Environmental consequences of future biogas technologies based on separated slurry. Environ. Sci. Technol. 45, 5869–5877. http://dx.doi.org/10.1021/es200273j.

Higarashi, M.M., Nicoloso, R.S., Oliveira, P.A.V., Mattei, R.M., 2013. Greenhouse gases emissions from deep pit stored swine manure in southern Brazil. In: III Simpósio Internacional sobre Gerenciamento de Resíduos Agropecuários e Agroindustriais – SIGER, São Pedro-SP, Brazil [online] Available from: http://www.sbera.org.br/3sigera/obras/pe_imp_05_MarthaHigarashi.pdf.

Hirschfeld, J., Weiß, J., Preisl, M., Korbun, T., 2008. Klimabilanz der Schweinefleischproduktion. In: Hirschfeld, J.W., Preisl, M., Korbun, T. (Eds.), Klimawirkungen der Landwirtschaft in Deutschland. IÖW [online] Available from: https://www.foodwatch.org/uploads/media/IOEW-Studie_Klimawirkungen_der_Landwirtschaft_in_Deutschland_2008_01.pdf.

Hutchings, N.J., ten Hoeve, M., Jensen, R., Bruun, S., Søtoft, L.F., 2013. Modelling the potential of slurry management technologies to reduce the constraints of environmental legislation on pig production. J. Environ. Manage. 130, 447–456. http://dx.doi.org/10.1016/j.jenvman.2013.08.063.

IBGE, 2012. Produção Pecuária Municipal 2012, vol. 40. Brazilian Institute of Geography and Statistics, Rio de Janeiro, p. 71 [online] Available from: ftp://ftp.ibge.gov.br/Producao_Pecuaria/Producao_da_Pecuaria_Municipal/2012/ppm2012.pdf.

ISO, 2006a. ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework. ISO Copyright Office, Geneva (Switzerland).

ISO, 2006b. ISO 14044: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. ISO Copyright Office, Geneva (Switzerland).

INPE, 2012. Monitoramento da floresta Amazônica brasileira por satélite – Estimativas Anuais de desflorestamento desde 1988 até 2012. National Institute of Spacial Research [online] Available from: http://www.obt.inpe.br/prodes/prodes_1988_2012.htm.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4, Agriculture, Forestry and Other Land Use. Chapter 10, Authors: Dong, H., Mangino, J. , Mcallister, T.A. , Hatfield, J.L. , Johnson, D.E. , Lassey, K.R. , de Lima, M.A. , Romanovskaya, A. Emissions from Livestock and Manure Management. Intergovernmental Panel on Climate Change. [online] Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf.

Kingston, C., Fry, J.M., Aumonier, S., 2009. Life Cycle Assessment of Pork. Final Report. Environmental Resources Management, Agriculture and Horticulture Development Board Meat Services – AHDBMS [online] Available from: http://www.bpex.org.uk/prices-facts-figures/documents/LifeCycelAssmntofPorklaunchversion.pdf.

Kool, A., Blonk, H., Ponsioen, T., Sukkel, W., Vermeer, H., de Vries, J.W., Hoste, R., 2009. Carbon Footprints of Conventional and Organic Pork: Assessment of Typical Production Systems in the Netherlands, Denmark, England and Germany. Blonk Milieu Advies BV, Netherland. November. [online] Available from: http://www.scp-knowledge.eu/sites/default/files/knowledge/attachments/BLONK%20Organic%20and%20conventional%20Porc%20meat.pdf.

Kunz, A., Higarashi, M.M., Oliveira, P.A.V., 2005. Tecnologias de manejo e tratamento de dejetos de suínos estudadas no Brasil. Cad. Ciênc. Tecnol. 22, 651–665 [online] Available from: https://seer.sct.embrapa.br/index.php/cct/article/viewFile/8663/4852.

Kunz, A., Miele, M., Steinmetz, R.L.R., 2009. Advanced swine manure treatment and utilization in Brazil. Bioresour. Technol. 100, 5485–5489. http://dx.doi.org/10.1016/j.biortech.2008.10.039.

Massé, D.I., Talbot, G., Gilbert, Y., 2011. On farm biogas production: a method to reduce GHG emissions and develop more sustainable livestock operations. Anim. Feed Sci. Technol. 166-167, 436–445. http://dx.doi.org/10.1016/j.anifeedsci.2011.04.075.

MMA, 2007. Projeto de conservação e utilização sustentável da diversidade biológica brasileira – PROBIO. Environment Ministry [online] Available from:

http://mapas.mma.gov.br/mapas/aplic/probio/datadownload.htm?/amazonia/dados/shape_file/folhas/vegetacao/.
Murphy, J.D., Mckeogh, E., Kiely, G., 2004. Technical/economical/environmental analysis of biogas utilisation. Appl. Energ. 77, 407–427. http://dx.doi.org/10.1016/j.apenergy.2003.07.005.
Nemecek, T., Kägi, T., 2007. Life Cycle Inventories of Swiss and European Agricultural Systems. Final report Ecoinvent v2.0 No. 15a. Agroscope Reckenholz-Taenikon Research Station ART, Swiss Centre for Life Cycle Inventories, Zurich and Dübendorf, CH [online] Available from: www.ecoinvent.ch.
Nguyen, T.L.T., Hermansen, J., Mogensen, L., 2011. Environmental Assessment of Danish Pork. Report n° 103. Aarhus University, Denmark [online] Available from: http://web.agrsci.dk/djfpublikation/djfpdf/ir_103_54761_indhold_internet.pdf.
Oliveira, P.A.V., 1993. Manual de manejo e utilização dos dejetos de suínos. EMBRAPA-CNPSA, Concórdia, p. 188 [online] Available from: http://www.infoteca.cnptia.embrapa.br/handle/doc/434003.
Oliveira, P.A.V., 2004. Tecnologias para o manejo de resíduos na produção de suínos: manual de boas práticas. In: Programa Nacional do Meio Ambiente – PNMA II. Embrapa Suínos e Aves, Concórdia-SC, p. 109 [online] Available from: http://www.cnpsa.embrapa.br/pnma/pdf_doc/doc_pnma.pdf.
Oliveira, P.A.V., Higarashi, M.M., 2006a. Unidade de compostagem para o tratamento dos dejetos de suínos. documento 114. Embrapa Suínos e Aves, p. 39 [online] Available from: http://www.cnpsa.embrapa.br/down.php?tipo=publicacoes&cod_publicacao=918.
Oliveira, P.A.V., Higarashi, M.M., 2006b. Geração e utilização de biogás em unidade de produção de suínos. documento 115. In: Programa Nacional do Meio Ambiente – PNMA II. Embrapa Suínos e Aves, p. 42 [online] Available from: http://www.cnpsa.embrapa.br/sgc/sgc_publicacoes/publicacao_l4l77t4r.PDF.
PRé Consultants, 2013. SimaPro Database Manual: Methods Library. Report version 2.5 [online] Available from: http://www.pre-sustainability.com/download/DatabaseManualMethods-oct2013.pdf.
Prudêncio da Silva, V., van der Werf, H.M.G., Soares, S.R., Spies, A., 2010. Variability in environmental impacts of Brazilian soybean according to crop production and transport scenarios. J. Environ. Manage. 91, 1831–1839. http://dx.doi.org/10.1016/j.jenvman.2010.04.001.
Prudêncio da Silva, V., 2011. Effects of Intensity and Scale of Production on Environmental Impacts of Poultry Meat Production Chains- LCA of French and Brazilian Poultry Production Scenarios. PhD thesis. Agrocampus Ouest – Université Européenne de Bretagne/Universidade Federal de Santa Catarina, Rennes, FR/Florianópolis, BR, p. 192 [online] Available from: www.ciclodevida.ufsc.br/arquivos/publicacoes/Tese_Vamilson-Prudencio%284f91a1d0b1c25%29.pdf.
Reckmann, K., Traulsen, I., Krieter, J., 2012. Environmental impact asssessment – methodology with special emphasis on European pork production. J. Environ. Manage. 107, 102–109. http://dx.doi.org/10.1016/j.jenvman.2012.04.015.
Reckmann, K., Traulsen, I., Krieter, J., 2013. Life cycle assessment of pork production: a data inventory for the case of Germany. Livest. Sci. 157, 586–596. http://dx.doi.org/10.1016/j.livsci.2013.09.001.
Rigolot, C., Espagnol, S., Robin, P., Hassouna, M., Béline, F., Paillat, J.M., Dourmad, J.Y., 2010. Modelling of manure production by pigs and NH_3, N_2O and CH_4 emissions. Part II: effect of animal housing, manure storage and treatment practices. Animal 4, 1413–1424. http://dx.doi.org/10.1017/S1751731110000509.
Ruviaro, C.F., Gianezini, M., Brandão, F.S., Winck, C.A., Dewes, H., 2012. Life cycle assessment in Brazilian agriculture facing worldwide trends. J. Clean. Prod. 28, 9–24. http://dx.doi.org/10.1016/j.jclepro.2011.10.015.
Schenck, R., 2006. Life Cycle Assessment of USA Pork Production in 2004. Institute for Environmental Research and Education – IERE.
Spies, A., 2003. The Sustainability of the Pig and Poultry Industries in Santa Catarina, Brazil: a Framework for Change. A Thesis Submitted for the Degree of Doctor of Philosophy. School of Natural and Rural Systems Management - University of Queensland, Brisbane, Australia.
Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock's Long Shadow. Environmental Issues and Options. LEAD, p. 390 [online] Available from: http://www.europarl.europa.eu/climatechange/doc/FAO%20report%20executive%20summary.pdf.
Tavares, J.M.R., Belli Filho, P., Coldebella, A., Oliveira, P.A.V., 2014a. The water disappearance and manure production at commercial growing-finishing pig farms. Livest. Sci. (in press) http://dx.doi.org/10.1016/j.livsci.2014.09.006.
Tavares, J.M.R., Belli Filho, P., Coldebella, A., Oliveira, P.A.V., 2014b. Efeito do tipo de bebedouro na produção de dejetos, e nos custos associados à sua estocagem, na suinocultura. In: Congreso Interamericano de Ingenieria Sanitaria y Ambiental, 34., Monterrey, 2014, Aceite para comunicação oral... (02 a 04 Novembro) Monterrey, México, 8 pp.
Thomassen, M.A., de Boer, I.J.M., 2005. Evaluation of indicators to assess the environmental impact of dairy production systems. Agric. Ecosyst. Environ. 111, 185–199. http://dx.doi.org/10.1016/j.agee.2005.06.013.
UNFCCC, 2012. Methane Recovery in Animal Manure Management Systems. United Nations Framework Convention on Climate Change. Clean Development Mechanism, version 19.0. [online] Available from: http://cdm.unfccc.int/about/index.html.
USDA, 2013. Livestock and Poultry: World Markets and Trade. 2014: Record Global Meat Trade. United States Department of Agriculture. Foreign Agricultural Service [online] Available from: http://apps.fas.usda.gov/psdonline/circulars/livestock_poultry.pdf.
Vallejo, A., Skiba, U.M., Garcia-Torres, L., Arce, A., Lopez-Fernandez, S., Sanchez-Martin, L., 2006. Nitrogen oxides emission from soils bearing a potato crop as influenced by fertilization with treated pig slurries and composts. Soil Biol. Biochem. 38, 2782–2793. http://dx.doi.org/10.1016/j.soilbio.2006.04.04.
van der Werf, H.M.G., Petit, J., 2002. Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agric. Ecosyst. Environ. 93, 131–145. http://dx.doi.org/10.1016/S0167-8809(01. http://dx.doi.org/10.1016/S0167-8809(01)00354-1.
Weidema, B.P., Wesnæs, M., Hermansen, J., Kristensen, I., Halberg, N., 2008. Environmental Improvement Potentials of Meat and Dairy Products. Institute for Prospective Technological Studies, JRC European Commission, p. 196 [online] Available from: http://ftp.jrc.es/EURdoc/JRC46650.pdf.
Wiedemann, S., Mcgahan, E., Grist, S., Grant, T., 2010. Environmental Assessment of Two Pork Supply Chains Using Life Cycle Assessment. Rural Industries Research and Development Corporation – RIRDC. Publication n° 09/176. [online] Available from: https://rirdc.infoservices.com.au/downloads/09-176.
Williams, A.G., Audsley, E., Sandars, D.L., 2006. Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Cranfield Unverstity and Defra, Bedford [online] Available from: www.silsoe.cranfield.ac.uk.