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Review

Review on greenhouse gas emissions from pig houses: Production of carbon dioxide, methane and nitrous oxide by animals and manure

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ABSTRACT

The environmental impacts of livestock production are attracting increasing attention, especially the emission of greenhouse gases (GHGs). Currently, pork is the most widely consumed meat product in the world, and its production is expected to grow in the next few decades. This paper deals with the production of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by animals and by manure from pig buildings, with a focus on the influence of rearing techniques and nutrition. GHG emissions in piggeries originate from animals through CO_2 exhalation and CH_4 enteric fermentation, and from manure through the release of CO_2, CH_4 and N_2O. The level of the CO_2 exhalation ($E\text{-}CO_{2,\ pig}$) depends on the physiological stage, the body weight (BW), the production level and the feed intake of the animals concerned. Enteric CH_4 ($E\text{-}CH_{4,\ pig}$) is principally related to dietary fibre intake and the fermentative capacity of the pig's hindgut. Based on a review of the literature, the following equations are proposed in order to estimate $E\text{-}CO_{2,\ pig}$ (in kg day^{-1}) and $E\text{-}CH_{4,pig}$ (in g day^{-1}) for fattening pigs: $E\text{-}CO_{2,\ pig} = 0.136 \times BW^{0.573}$; $E\text{-}CH_{4,pig} = 0.012 \times dRes$; with BW (in kg) and dRes for digestible residues (in g day^{-1}). Numerous pathways are responsible for GHG production in manure. In addition, the microbial, physical and chemical properties of manure interact and modulate the level of emissions. Influencing factors for removal systems for both liquid and solid fractions of manure have been investigated. A large range of parameters showing an impact on the level of GHG production from pig houses has been reported. However, few of these can be considered unquestionably as GHG mitigation techniques because some strategies have shown contradictory effects depending on the gas, the circumstances and the study. Nevertheless, frequent manure removal seems to be an efficient means to reduce concurrently CO_2-, CH_4- and N_2O-emissions from pig buildings for both slatted and bedded floor systems. Manure removal operations may be associated with specific storage conditions and efficient treatment in order to further reduce emissions. Several feeding strategies have been tested to decrease GHG emissions but they seem to be ineffective in reducing emissions both significantly and durably. In general, good management practices that enhance zootechnical performance will have beneficial consequences on GHG emission intensity. Taking into account the results described in the literature regarding CO_2-, CH_4- and N_2O-production from animals and manure in pig houses, we estimate total GHG emissions to 448.3 kg CO_2equiv. per slaughter pig produced or 4.87 kg CO_2equiv. per kg carcass. The fattening period accounts for more than 70% of total emissions, while the gestation, lactation and weaning periods each contribute to about 10% of total emissions. Emissions of CO_2, CH_4 and N_2O contribute to 81, 17 and 2% of total emissions from pig buildings, representing 3.87, 0.83 and 0.11 kg CO_2equiv. per kg carcass, respectively.

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1. Introduction

Globally, livestock production accounts for 18% of anthropogenic emissions of greenhouse gases (GHGs) (Steinfeld et al., 2006). Pork is the most widely consumed meat product in the world, and pig production is the second contributor of GHG emissions from livestock sector, with about 13% of total emissions being related to livestock (Tables 1 and 2; FAO, 2011). By 2050, worldwide pork consumption is expected to increase by almost 40% (FAO, 2011). Most of that increase in consumption will occur in developing countries, owing to demographic growth, changes in food preferences and better access to food due to the intensification of livestock systems close to growing urban populations (FAO, 2011). Presently, industrial farm animal production systems account for over half of pork production, and developing countries contribute to about half of this industrial production (Steinfield et al., 2006). In the future, these shares are expected to grow dramatically. Therefore, the environmental impact of industrial pig production represents a crucial issue for consideration in ensuring sustainability in meat production. Moreover, reducing GHG emissions would mitigate the adverse effects of GHGs on global climate change (increased temperature, higher sea level, drought, soil erosion and loss of global crop productivity) (IPCC, 2007).

Within this context, this paper aims to study the factors that influence the production levels of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by animals and manure at pig house level. Emissions associated with feed production, land use and land use change, energy consumption, manure spreading, transportation and food processing are not included in this discussion. Emissions associated with outside manure storage and manure treatments are also outside the scope of this review. These issues will, nevertheless, be briefly touched upon due to the link with emissions released from pig buildings. Direct CO_2 emissions from animals and from manure are usually excluded from GHG assessment because it is assumed that they are compensated by CO_2 consumption through the photosynthesis of plants used as feed. Consequently, CO_2 production by animals and by manure is rarely addressed in the literature. However, these CO_2 emissions at house level are not negligible and may differ from one rearing system to another (Philippe et al., 2007a,b). Moreover, since the synthesis pathways of carbon compounds are interlinked, it seems relevant to consider CO_2 and CH_4 emissions comprehensively. Indeed, a significant reduction in one gas could be compensated by an increase in another. Thus, the choice has been made to include CO_2 emissions in this paper in order to avoid any errors of judgement in assessing the environmental effect of a particular type of GHG mitigation technique.

The paper is organized as follows. Firstly, it describes the processes that are responsible for the production of CO_2, CH_4 and N_2O by animals and by manure at pig house level. Secondly, emission factors reported in the literature are reviewed according to the physiological stages of pig development, and an overall emission factor is proposed for the complete pig production process. Finally, the effects of pig rearing conditions (including dietary factors) on emissions are studied and some mitigation techniques are described.

2. Sources of emissions

2.1. Carbon dioxide

The emissions of CO_2 from pig houses come from two sources: exhalation by pigs and release from manure.

2.1.1. Exhalation by pigs

CO_2 production during respiration is related to the respiratory quotient, defined as the ratio between the volume of CO_2 production and the volume of oxygen consumption. In practice,

Table 1
Projected human population (in billion people) and global meat consumption (in million tons) from 2010 to 2050.
Source: adapted from FAO, 2011.

	2010	2020	2030	2050	Growth 2010–2050
Human population	6.91	7.67	8.31	9.15	+32%
Meat consumption					
Pig meat	102.3 (38%)	115.3 (36%)	129.9 (34%)	140.7 (30%)	+38%
Poultry meat	85.9 (32%)	111.0 (35%)	143.5 (38%)	193.3 (42%)	+125%
Bovine meat	67.3 (25%)	77.3 (24%)	88.9 (23%)	106.3 (23%)	+58%
Sheep/goat meat	13.2 (5%)	15.7 (5%)	18.5 (5%)	23.5 (5%)	+78%
All meat	268.7 (100%)	319.3 (100%)	380.8 (100%)	463.8 (100%)	+73%

Table 2
Contribution of livestock species to global greenhouse gas emissions.
Source: adapted from Steinfeld et al., 2006; FAO, 2013a,b.

Species	Greenhouse gas emissions (million tons CO_2equiv. year^{-1})			
	CO_2 emissions	CH_4 emissions	N_2O emissions	Total emissions
Cattle	1166.2 (61%)	2072.8 (81%)	661.6 (60%)	3900.6 (70%)
Small ruminants	69.9 (4%)	244.5 (10%)	202.6 (18%)	517.0 (9%)
Pigs	338.9 (18%)	237.3 (9%)	131.1 (12%)	707.3 (13%)
Poultry	332.2 (17%)	–	107.3 (10%)	439.5 (8%)
Total	1907.2 (100%)	2554.5 (100%)	1102.6 (100%)	5564.3 (100%)

CO_2equiv.: emissions of CO_2-equivalents, including CO_2, CH_4 and N_2O, taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively.

the respiratory quotients reported in the literature are around 1.10 for growing pigs, around 1.00 for piglets and around 0.90 for reproductive sows (Moehn et al., 2004; Pedersen et al., 2008; Atakora et al., 2011b). CO_2 exhalation can also be derived from animal heat production (HP), which corresponds to the energy used for maintenance, production (growth or milk production) and thermoregulation (Noblet et al., 1989). The International Commission of Agricultural Engineering (CIGR, 2002) stated that HP should be estimated by taking into account the pig's body weight (BW), the production level and the feed energy intake. The production of respiratory CO_2- can be derived from these models, and corresponds to 2.23, 3.68, 0.88 and 1.70 kg CO_2 head^{-1} day^{-1} for gestating sows, lactating sows, weaned piglets and fattening pigs, respectively (CIGR, 2002). Other experiments have been carried out to measure or estimate CO_2 exhalation from practical parameters. Models developed for fattening pigs are presented in Table 3 and illustrated in Fig. 1. In cases of a lack of data, models were simplified to express the CO_2 exhalation function of BW, according to data obtained by Aubry et al. (2004). An aggregation of the models reported in Table 3 gives the following equation proposed to predict CO_2 exhalation (E-$CO_{2,\ pig}$, in kg CO_2 day^{-1}) for pigs of 20–120 kg BW (Fig. 1; $R^2 = 0.91$):

$$E - CO_{2,\ pig} = 0.136\ BW^{0.573} \quad (1)$$

Thus, respiratory CO_2 production can be estimated to about 1.55 kg day^{-1} for a pig of 70 kg BW.

2.1.2. Release from manure

For many years, levels of CO_2 emissions from manure were believed to be negligible (Anderson et al., 1987; van 't Klooster and Heitlager, 1994). According to some recent research, the levels of CO_2 released from manure have been estimated to be 4–5% of the CO_2 exhaled by animals (CIGR, 2002; de Sousa and Pedersen, 2004; Dong et al., 2007). However, some authors have reported CO_2 release accounting for 10–30% of respiratory production (Jeppsson, 2000, 2002; Philippe et al., 2007a,b; Pedersen et al., 2008; Philippe et al., 2012a). During an experiment carried out in a commercial fattening unit, emissions from manure were evaluated to be at around 40% of the tranquil CO_2 exhalation rate (Ni et al., 1999b). The production of CO_2 from manure certainly needs to be taken into account, even though it is not the main source of CO_2 in pig houses.

In manure, CO_2 originates from three sources: (1) the rapid hydrolysis of urea into NH_3 and CO_2 catalysed by the enzyme urease; (2) the anaerobic fermentation of organic matter into intermediate volatile fatty acids (VFAs), CH_4 and CO_2; (3) the aerobic degradation of organic matter (Jeppsson, 2000; Moller et al., 2004; Wolter et al., 2004). For liquid manure, anaerobic processes have been frequently considered as the main source of CO_2 (Ni et al., 1999b). However, this conclusion is contradictory to the results of Moller et al. (2004), who observed under laboratory conditions that aerobic and anaerobic processes are of almost equal importance at a temperature of 20 °C, while a lower temperature (15 °C) favoured the aerobic processes. Moreover, crust formation at the surface of the slurry can also lead to CH_4 oxidation into CO_2 during the passage through the porous areas of the crust.

For solid manure, the principal origin of CO_2 is aerobic production, the so-called composting process, performed by a mesophilic/thermophilic microbial community that converts degradable organic matter (Hellmann et al., 1997; Wolter et al., 2004). The composting process is influenced by several factors, such as temperature, moisture content, carbon/nitrogen ratio, degradability of carbon compounds, pH level and the physical structure of the organic material (Andersson, 1996; Jeppsson, 2000; Paillat et al., 2005).

2.2. Methane

Methane originates from the anaerobic degradation of organic matter performed by bacteria in the digestive tract of the pigs and in the manure.

2.2.1. Enteric fermentation

The level of enteric CH_4 production is mainly determined by the fibre content of the diet and the fermentative capacity of the pig's hindgut. Thus, increased levels of dietary fibre are associated with increased CH_4 production, while fermentative capacity depends on the physiological stage of the pigs, with typically higher CH_4 production for adult pigs (Le Goff et al., 2002a).

Table 3
Equations proposed to estimate CO_2 exhalation by fattening pigs (E-$CO_{2,\ pig}$, in kg day^{-1}) according to body weight (BW, in kg).

References	Equations	Methodology
Müller and Schneider (1985)	$E - CO_{2,\ pig} = 0.114\ BW^{0.588}$	Pigs in metabolic crates (from 20 to 110 kg)
Feddes and DeShazer (1988)	$E - CO_{2,\ pig} = 0.136\ BW^{0.549}$	Data derived from feed intakes
van 't Klooster and Heitlager (1994)	$E - CO_{2,\ pig} = 2.88 \times 10^{-2} \times BW^{0.75} + 8.29 \times 10^{-2} \times BW^{0.549}$	Data derived from feed intakes
Ni et al. (1999a)	$E - CO_{2,\ pig} = 0.224\ BW^{0.46}$	Field measurements in a commercial fattening pig house
Brown-Brandl et al. (2004)	$E - CO_{2,\ pig} = 0.123\ BW^{0.62}$	Literature review
Pedersen et al. (2008)	$E - CO_{2,\ pig} = 0.0998\ BW^{0.646}$	Literature review
This review	$E - CO_{2,\ pig} = 0.136\ BW^{0.573}$	Literature review

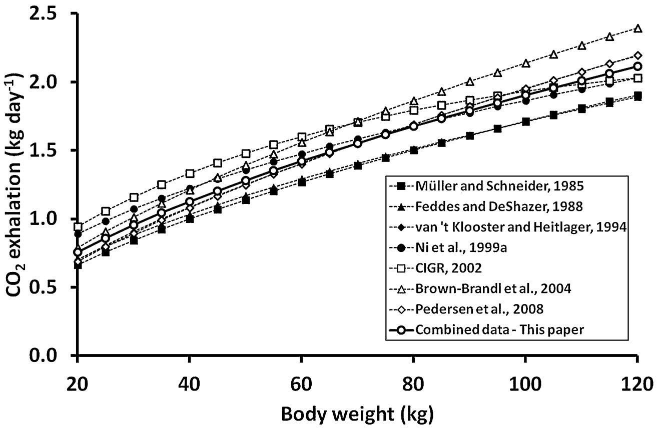

Fig. 1. Carbon dioxide (CO_2) exhalation by pigs estimated according to body weight.

Greater enteric production by sows can be explained by several factors, including increased feeding capacity, better intrinsic ability of bacterial flora to digest fibre, a greater number of bacteria, a reduction in the relative feeding level, and increased transit time (Le Goff et al., 2002a). Fig. 2 illustrates the production of enteric CH_4 for fattening pigs and adult sows reported in the literature according to the level of fibre intake, the so-called digestible residues (dRes), as proposed in INRA-AFZ (2004) and defined as the difference between digested organic matter and digested protein, fat, starch and sugar. By compiling these data, the following equations have been developed to predict the CH_4 enteric production (E-$CH_{4,\mathrm{pig/sow}}$, in g CH_4 day^{-1}) from dRes intakes (g day^{-1}) for fattening pigs (Eq. (2)) and for adult sows (Eq. (3)):

$$\mathrm{E}-\mathrm{CH}_{4,\mathrm{pig}} = 0.012 \times \mathrm{dRes}(R^2 = 0.77) \tag{2}$$

$$\mathrm{E}-\mathrm{CH}_{4,\mathrm{sow}} = 0.021 \times \mathrm{dRes}(R^2 = 0.90) \tag{3}$$

For example, the ingestion of 300 g of dRes is associated with the enteric production of 3.6 g CH_4 by fattening pigs and 6.3 g CH_4 by adult sows. Enteric emissions represent energy losses of 56.65 kJ per g of CH_4 produced, which represents about 0.4–0.5% of digestible energy (DE) for fattening pigs and 1.0–1.5% DE for adult sows. According to the tier 1 methodology from the IPCC guidelines for national inventories (IPCC, 2006), enteric CH_4 is estimated at 1.5 kg per head per year, corresponding to 4.1 g CH_4 day^{-1}, whatever the diet composition and physiological stage. Taking into account conventional diet composition, level of ingestion and/or growth performance Vermorel et al. (2008) estimated for French production daily enteric CH_4 emissions to 0.8, 2.4 and 8.2 g CH_4 head^{-1} for weaned piglets (up to 20 kg), fattening pigs (from 20 kg) and reproductive sows, respectively. Corresponding values for German production were proposed by Dämmgen et al. (2012a) at 0.9, 2.5 and 6.1 g CH_4, respectively.

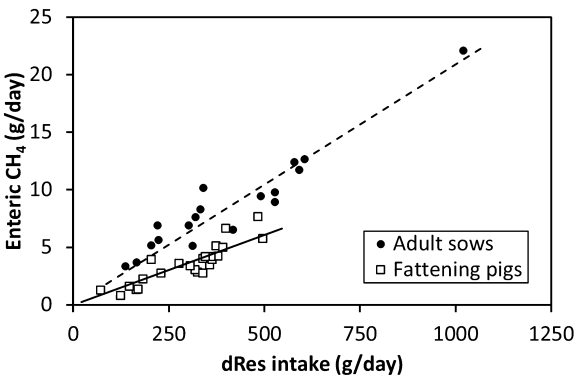

Fig. 2. Estimations of enteric methane (CH_4) production by adult sows and fattening pigs according to the intake of digestive residues (dRes defined as the difference between digested organic matter and digested protein, fat, starch and sugar).Source: adapted from Noblet et al., 1994; Jorgensen et al., 1996; Olesen and Jorgensen, 2001; Le Goff et al., 2002a,b; Ramonet et al., 2000; Galassi et al., 2004, 2005; Jorgensen, 2007; Jorgensen et al., 2007; Serena et al., 2008.

2.2.2. Release from manure

The release of CH_4 from manure originates from the temporal succession of microbial processes (Hellmann et al., 1997; Monteny et al., 2006). Initially, unspecified bacteria convert easily degradable substrates into VFAs, CO_2 and H_2. This extensive microbial activity increases the temperature of the manure and provides suitable conditions for methanogenic bacteria to convert acetate, CO_2 and H_2 into methane under a thermophilic environment. Factors that favour CH_4 production are lack of oxygen, high temperature, a high level of degradable organic matter, high moisture content, a low redox potential, a neutral pH, and a C/N ratio of between 15 and 30 (Moller et al., 2004; Amon et al., 2006; Kebreab et al., 2006).

According to the guidelines for National Greenhouse Gas Inventories (IPCC, 2006), CH_4 emissions from manure (E-$CH_{4,\mathrm{manure}}$, in m^3) can be estimated based on the amount of excreted volatile solid (VS) or organic matter (OM), in kg; the ultimate CH_4 potential (B_0), in m^3 CH_4 per kg VS or OM; and the methane conversion factor (MCF), in percentage:

$$\mathrm{E}-\mathrm{CH}_{4,\,\mathrm{manure}} = \mathrm{VS} \times B_0 \times \mathrm{MCF}$$

The IPCC (2006) recommends values for VS, B_0 and MCF, depending on the region of the world, the climate, the livestock categories and the type of manure. In Western Europe, the recommended value for VS is 0.30 kg pig^{-1} day^{-1} (IPCC, 2006). In the literature, B_0 values vary from 0.29 to 0.53 m^3 per kg VS or OM (Moller et al., 2004; Chae et al., 2008; Vedrenne et al., 2008; Jarret et al., 2011; Dämmgen et al., 2012b). The B_0 value proposed by the IPCC (2006) is 0.45 m^3 per kg VS. In the literature, extreme MCF values range from 2% to 80% according to manure type, manure management, storage duration, diet composition and temperature (Moller et al., 2004; Jarret et al., 2011; Dämmgen et al., 2012b; Rodhe et al., 2012). In their study, Moller et al. (2004) showed that during long-term storage (90 days), the slurry MCF value increased from 5.3 to 31.3% at temperatures ranging from 15 to 20 °C, respectively. On the other hand, at high temperatures, reducing the storage duration from 90 to 30 days decreased the MCF to 10.9%. Taking into account the proportion of manure management system usage, the emission factor for gas releases from swine manure in temperate Western Europe is estimated to 12 kg CH_4 head^{-1} year^{-1}, or 32.9 g CH_4 day^{-1}, including inside and outside storage (IPCC, 2006).

2.3. Nitrous oxide

In pig houses, N_2O originates only from manure. Its formation mainly occurs during incomplete nitrification/denitrification processes performed by micro-organisms that normally convert NH_3 into non-polluting molecular nitrogen (N_2). The main microbial pathways involved in N_2O synthesis are presented in Fig. 3. An abiotic conversion of ammonium under acidic conditions, so-called chemo-denitrification, can also be at the origin of N_2O (Oenema et al., 2005; Petersen and Miller, 2006).

Nitrification, the process that converts ammonia into nitrate (NO_3^-), is usually carried out by autotrophic bacteria that require aerobic conditions with a pH value of above 5 (Kebreab et al., 2006). During nitrification, N_2O is synthesized as a by-product when there is a lack of oxygen and/or a nitrite accumulation. Denitrification is the reduction of NO_3^- into N_2, with many

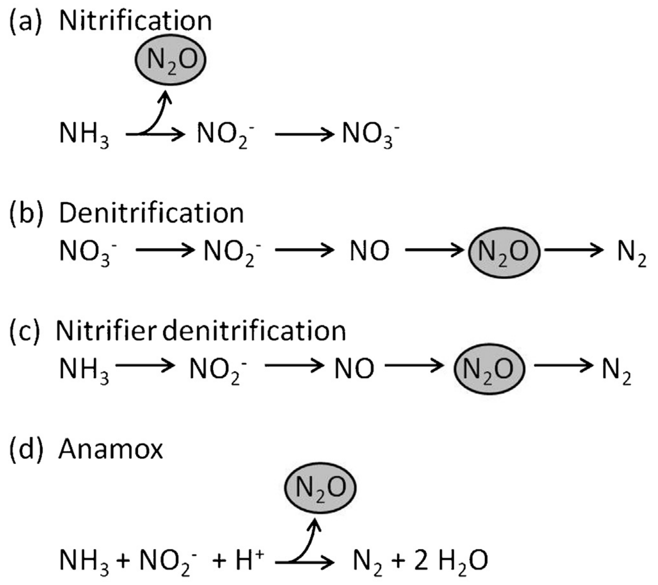

Fig. 3. Microbial pathways involved in N_2O synthesis in manure.

intermediate compounds being produced during the process (NO_2^-, nitric oxide (NO), and N_2O). In manure, denitrification is principally performed by heterotrophic facultative aerobic bacteria. The accumulation of N_2O in manure is favoured in the presence of oxygen and/or low availability of degradable carbohydrates (Poth and Focht, 1985; Driemer and Van den Weghe, 1997). The production of N_2O can also occur during other microbial pathways: the oxidation of ammonium under aerobic or anaerobic conditions, the so-called nitrifier denitrification and anamox processes, respectively. Most nitrifying and denitrifying microorganisms are mesophilic, and thus, the formation of N_2O is generally inhibited by temperatures above 40–50 °C (Hellmann et al., 1997; Kebreab et al., 2006). However, some authors have detected N_2O synthesis under thermophilic conditions (Wolter et al., 2004; Szanto et al., 2007). The relative contribution of these numerous pathways has still to be determined. Nevertheless, N_2O synthesis is known to require a close combination of aerobic and anaerobic areas. These heterogeneous conditions are largely encountered within litter but are rarer in slurry. However, N_2O emissions can occur from slurry when a dry crust is formed on the surface containing a combination of anaerobic and aerobic micro-sites. In any case, N_2O production from manure has a highly stochastic nature, especially due to its numerous sources of emission and environmental controls.

The guidelines for National Greenhouse Gas Inventories (IPCC, 2006) recommend estimating direct N_2O emissions by multiplying N excreted by animals (N_{ex}) by a specific conversion factor for each type of manure management system. For example, this conversion factor is 0.2% N_{ex} for pit storage under animals and 1% N_{ex} for deep bedding. Assuming 40 g N_{ex} pig^{-1} day^{-1}, this represents 0.13 and 0.63 g N_2O pig^{-1} day^{-1}, respectively.

3. Contribution by physiological stage

Several authors have measured GHG emissions from pig houses under practical conditions. Table 4 summarizes results from

Table 4
Emission factors at house level for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) related to the physiological stage of the pigs (kept on a slatted floor).

Physiological stage	Country	Greenhouse gas emissions (kg CO_2equiv. LU^{-1} day^{-1})			
		CO_2	CH_4	N_2O	Total
Gestating sows					
Lägue et al., 2004	Canada	11.98	2.13	0.00	14.10
Dong et al., 2007	China	5.92	0.24	0.22	6.38
Zhang et al., 2007	USA	8.16	2.39	0.00	10.55
Costa and Guarino, 2009	Italy	8.85	3.30	0.81	12.96
Philippe et al., 2011a	Belgium	5.70	0.60	0.33	6.63
Stinn et al., 2011	USA	8.95	7.07	0.03	16.04
Mean		8.26	2.62	0.23	11.11
Farrowing sows					
Lägue et al., 2004	Canada	21.50	4.56	0.00	26.06
Dong et al., 2007	China	7.49	0.24	0.16	7.89
Zhang et al., 2007	USA	14.08	6.69	0.00	20.77
Stinn et al., 2011	USA	27.86	3.59	0.07	31.53
Mean		17.73	3.77	0.06	21.56
Weaned piglets					
Lägue et al., 2004	Canada	29.85	14.69	0.00	44.54
Dong et al., 2007	China	29.67	1.46	0.38	31.51
Cabaraux et al., 2009	Belgium	10.70	0.74	0.05	11.48
Costa and Guarino, 2009	Italy	6.00	0.61	1.08	7.69
Mean		19.05	4.37	0.38	23.81
Fattening pigs					
Nicks et al., 2005	Belgium	13.86	3.24	0.75	17.85
Dong et al., 2007	China	16.73	0.80	0.26	17.79
Philippe et al., 2007a	Belgium	12.84	3.01	1.19	17.04
Costa and Guarino, 2009	Italy	13.64	4.75	0.97	19.35
Palkovicova et al., 2009	Slovak Republic	14.36	5.76	0.91	21.02
Guingand et al., 2010	France	17.82	1.95	0.47	20.24
Li et al., 2011	USA	16.20	0.53	1.71	18.44
Ngwabie et al., 2011	Sweden	16.38	3.78	0.37	20.53
Mean		15.23	2.98	0.83	19.03

CO_2equiv.: emissions of CO_2-equivalents, including CO_2, CH_4 and N_2O, taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively.
LU: livestock unit, equal to 500 kg BW. In cases of a lack of data, default values for body weight (BW) were estimated to 200, 220, 18 and 70 kg for gestating sows, farrowing sows (including piglets), weaned piglets and fattening pigs, respectively.

research involving the study of CO_2, CH_4 and N_2O together for pigs kept on slatted floors at their different physiological stages. In order to facilitate a comparison between physiological stages and between gases, emissions are expressed in the table as CO_2-equivalents per livestock unit. The CO_2-equivalents (CO_2equiv.) take into account the global warming potential of each gas, which is evaluated to 25 and 298 times that of CO_2 over a 100-year period for CH_4 and N_2O, respectively (IPCC, 2007). The livestock unit (LU) is equal to 500 kg body weight.

The CO_2 emissions related to fattening pigs are quite similar between the studies, while the corresponding values for the other physiological stages shows greater variation, especially for weaned piglets. Similar findings have also been observed by Philippe et al. (2011b) regarding NH_3 emissions. The discrepancy between the results of the studies, as shown in Table 4, may be attributed to differences in housing conditions, ventilation systems, management practices, diet formulation and gas measurement method. Nevertheless, the average emission factors proposed by physiological stage seem consistent between the studies. Indeed, gestating sows present the lowest value (8.26 kg CO_2 LU^{-1} day^{-1}, or 3.3 kg CO_2 sow^{-1} day^{-1}), as influenced by their low feed intake (restricted feeding, low energy density of the diet) and metabolism. Farrowing sows (including piglets) and weaned piglets are associated with the highest emissions (17.73 kg CO_2 LU^{-1} day^{-1}, or 8.87 kg CO_2 sow^{-1} day^{-1}, and 19.05 kg CO_2 LU^{-1} day^{-1}, or 0.69 kg CO_2 pig^{-1} day^{-1}, respectively), as a consequence of ad libitum feeding and intensive productive status (milk production and growth). Emissions related to fattening pigs (15.3 kg CO_2 LU^{-1} day^{-1}, or 2.1 kg CO_2 pig^{-1} day^{-1}) are slightly lower than the latter.

The CH_4 emissions reported in the literature present a large range of variation within each physiological stage. In addition to the variation factors described above for CO_2, the manure removal strategy and the storage duration inside the building seem to play an important role regarding the level of emissions (see below). For the other physiological stages, higher emissions were also observed with a longer duration of indoor manure storage. Table 4 shows that, on average, the mean emission factors expressed per LU do not differ significantly between physiological stages, ranging from 2.62 kg CO_2equiv. LU^{-1} day^{-1} for gestating sows, to 4.37 kg CO_2equiv. LU^{-1} day^{-1} for weaned piglets, with intermediate values for fattening pigs (2.98 kg CO_2equiv. LU^{-1} day^{-1}) and farrowing sows (3.77 kg CO_2equiv. LU^{-1} day^{-1}). Corresponding values expressed per animal are 41.9, 6.3, 16.7 and 78.5 g CH_4 day^{-1}, respectively. The CH_4 emissions associated with gestating sows could be deemed quite low, considering the high fibre content of their diet and their large fermentative capacity. In fact, these effects are counterbalanced by the restricted feeding usually applied at this stage.

As can be seen in Table 4, the N_2O emissions measured from pig houses fitted with a slatted floor were relatively low whatever the pigs' physiological stage. In some experiments (Lägue et al., 2004; Zhang et al., 2007), the production of N_2O emissions was even lower than the detection limit of the measurement equipment, giving small mean values as a result. In this context, important relative differences between studies or physiological stages do not have significant meaning. Thus, it seems more appropriate to consider a generic emission factor for all the stages. Based on the values reported in Table 4, an average emission of 0.40 kg CO_2equiv. LU^{-1} day^{-1} could be proposed.

Also based on these values, total GHG emissions from pig buildings are estimated to 11.11 kg CO_2equiv. $LU^{-1}day^{-1}$ for gestating sows and around 20 kg CO_2equiv. $LU^{-1}day^{-1}$ for lactating sows, weaned piglets and fattening pigs, reflecting the relative metabolism rate of each physiological stage.

The contribution of each physiological stage to GHG emission intensity expressed per unit of product is estimated using the data from Table 4 and is presented in Table 5. Overall, GHG emissions from pig houses are estimated to 448.4 kg CO_2equiv. per slaughter pig produced or 4.87 kg CO_2equiv. per kg carcass. The fattening period accounts for more than 70% of total emissions, while the gestation, lactation and weaning periods each contribute to about 10% of total emissions. Thus, it can be concluded that efforts to reduce emissions should primarily target fattening pigs. Emissions of CO_2, CH_4 and N_2O contribute to 81, 17 and 2% of total emissions from buildings, representing 3.87, 0.83 and 0.17 kg CO_2equiv. per kg carcass, respectively. These figures show the important share of CO_2 in global emissions contributed by pigs and their manure. However, these sources of emission are usually neglected in GHG evaluation. Indeed, several authors have developed life cycle assessment (LCA) studies to estimate the intensity of emissions given off in pig production. These models exclude CO_2 emissions from respiration and manure but include GHG emissions for feed production, manure storage and spreading, and energy consumption. Reported values range from 3.07 to 5.79 kg CO_2equiv. per kg carcass (Vergé et al., 2009; Pelletier et al., 2010; Lesschen et al., 2011; Weiss and Leip, 2012). The discrepancy between these studies comes from the differences in methodology, type of pig production, boundaries of the system, emission categories and allocation.

4. Influencing factors

The GHG emissions from pig houses are principally influenced by floor type, manure management and nutrition of the pigs. The climatic conditions inside the building also impact emission levels.

Table 5
Contribution of the physiological stage of pigs on greenhouse gas emissions per unit of product (assuming no allocation to slaughter by-products).

Physiological stage	Days	Greenhouse gas emissions (kg CO_2equiv.[a])		
		Day^{-1} $animal^{-1}$[b]	Slaughter pig^{-1}[c]	kg $carcass^{-1}$[d]
Dry and gestating sows	125	4.44	55.6	0.60 (12%)
Lactating sows[e]	28	10.78	30.2	0.33 (7%)
Weaned piglets[f]	50	0.86	42.8	0.47 (10%)
Fattening pigs[g]	120	2.67	319.9	3.48 (71%)
Total	323	–	448.4	4.87 (100%)

[a] CO_2equiv.: CO_2-equivalent, including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively.
[b] Derived from data presented in Table 4.
[c] Based on 10 slaughtered pigs per litter.
[d] Based on carcass weight of 92 kg (liveweight of 118 kg and dressing percentage of 78%).
[e] Including piglets of up to 8 kg BW.
[f] From 8 to 28 kg BW with 400 g of average daily gain.
[g] From 28 to 118 kg BW with 750 g of average daily gain.

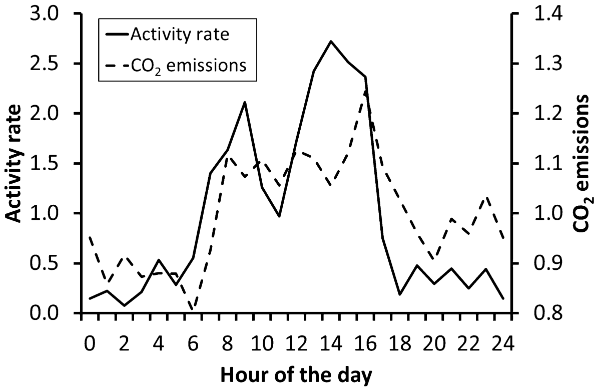

Fig. 4. Nycthemeral evolution around the daily mean (value = 1) of the activity rate of pigs and the carbon dioxide emissions associated with fattening pigs kept on a slatted floor.Source: adapted from Philippe et al., 2013.

4.1. Climatic conditions

Gaseous emissions are positively related to temperature and ventilation rate. An experiment carried out in a commercial pig house emptied of pigs showed that CO_2 emissions from slurry doubled when the manure temperature increased from 15 to 20 °C, and increased from 0.8 to 25.8 g CO_2 h^{-1} per m^2 of slurry when the ventilation rate ranged from 160 to 3350 m^3 h^{-1} (Ni et al., 1999b). Ngwabie et al. (2011) reported that CH_4 emissions doubled when the indoor temperature in a fattening pig unit increased from 16.8 to 22.8 °C. Blanes-Vidal et al. (2008) estimated the correlation between averaged ventilation flow and CH_4 emission to be 0.79 on an hourly basis.

Typically, gaseous emissions from pig houses present a diurnal pattern as a consequence of the comprehensive effects of temperature, ventilation rate and animal activity. The highest emission rates are usually observed during feeding time (Van Milgen et al., 1997; Moehn et al., 2004). For fattening pigs fed ad libitum, a first peak of emission occurs in the morning and a second peak in the afternoon, as illustrated for CO_2 emissions in Fig. 4 (adapted from Philippe et al., 2013). Modification of the feeding schedule can have an impact on the level of daily emissions, as demonstrated by Groenestein et al. (2003) with gestating sows.

The location of the fans in the building also contributes to a modulation of the emission levels. Air inlets or outlets located near the manure surface increase the level of emissions due to greater air flow at the interface (Hayes et al., 2006). In any case, using climate conditions to modulate the release of GHGs seems rather impractical since the ambient parameters must primarily respect the physiological needs of the animals. Nevertheless, optimization of the heating and ventilation in the housing system can have a beneficial effect on emission levels. Good practice includes insulation of the building, adaptation to internal (e.g. density of the pigs and their physiological stage) and external factors (e.g. season and weather), management of air circulation and regular monitoring of the ventilation devices. Regulation of climatic parameters also has an influence on the health, performance, welfare and behaviour of the pigs, thereby causing indirect effects on the level of emissions. In addition, energy saving related to optimal management of climatic factors can be considered environmentally and economically beneficial.

4.2. Floor type and manure management

In pig production, the most frequent housing conditions are based on a slatted floor with a deep pit underneath for the storage of slurry. Alongside this traditional system, bedded systems have met with renewed interest during recent decades, as these systems are related to improved welfare, reduced odour nuisance and a better brand image for livestock production. For both housing systems, a large range of parameters may influence the levels of GHG emissions.

4.2.1. Slatted floor systems

4.2.1.1. Proportion of the slatted area. It is usually assumed that the emission of pollutant gases can be reduced by lowering the slurry emitting surface. With the implementation of a partly slatted floor, some authors have observed a reduction in CO_2 production by 7–13% compared with a fully slatted floor, confirming that slurry is not the main source of emission (Table 6; Sun et al., 2008; Guingand et al., 2010). For CH_4 production, contradictory results have been reported in the literature, with decreased emissions (Lägue et al., 2004; Philippe et al., 2014a) or increased emissions being associated with partly slatted floors (Guingand et al., 2010). The effect of a slatted floor area on N_2O emissions has also shown conflicting results (Fitamant et al., 1999; Lägue et al., 2004; Guingand et al., 2010; Philippe et al., 2014a). In any case, absolute N_2O emissions from slurry have been shown to remain quite low, whatever the type of slatted floor. Cumulative emissions of GHGs (expressed in CO_2-equiv.) have been shown to be reduced by 4–13% by the application of a partly slatted floor compared with a fully slatted floor (Table 6).

Costs associated with partly slatted floors are quite similar to those of fully slatted floors despite a slightly higher labour cost due to pen fouling and the need for additional cleaning (Krieter, 2002). Application of partly slatted floors in existing fully slatted buildings is rather limited. Solid plates can be easily placed on the floor to create a partly slatted floor, but the total surface of the pit will remain unchanged, with no potential effects on emissions.

4.2.1.2. Slurry removal strategy. The increase in the slurry level could favour emissions, since it has been suggested that a smaller space between the slats and the surface of manure increases air turbulence and the release of gases (Ye et al., 2009). However, several authors have reported that a higher slurry depth does not

Table 6
Effect of the proportion of slatted floor (fully or partly slatted floor) on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively) associated with fattening pigs.

References	Fully slatted floor				Partly slatted floor			
	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)
Fitamant et al., 1999	–	–	1.10	–	–	–	1.59	–
Lägue et al., 2004	6.00	28.0	0.07	6.72	5.88	15.6	0.00	6.27
Sun et al., 2008	3.38	–	–	–	2.95	–	–	–
Guingand et al., 2010	2.48	9.7	0.19	2.78	2.31	11.2	0.24	2.66
Philippe et al., 2014a	1.45	5.4	0.23	1.64	1.46	4.8	0.21	1.65

promote the release of gases (Lägue et al., 2004; Haeussermann et al., 2006).

Nevertheless, frequent removal of manure has been proposed as a means to diminish the release of emissions from pig buildings. Total emissions within outside storage will also be reduced provided the temperature is lower outside than inside or where specific manure treatments are applied. In their study of CH_4 and N_2O emissions from pig units, Osada et al. (1998) showed that weekly removal of manure reduced the level of these emissions by about 10% compared with the traditional deep-pit system. With the same removal strategy, Guarino et al. (2003) observed a reduction of 19% in CH_4 emissions, but a doubling of N_2O emissions. Yet cumulative emissions (expressed in CO_2-equiv.) were shown to be lowered by 16%. Lavoie et al. (2006) found that when manure was removed three times a week instead of only once, CH_4 emissions were reduced by 16% and N_2O emissions remained insignificant. Results from these three studies regarding CO_2 emissions would suggest that the level of these emissions is not impacted by the removal frequency of manure (Osada et al., 1998; Guarino et al., 2003; Lavoie et al., 2006).

Pit flushing is also an efficient means to mitigate emissions. Sommer et al. (2004) estimated to 35% the reduction potential of cumulative GHGs (CH_4 and N_2O) with daily flushing compared with having a static pit. By combining frequent flushing (six times a day) with a reduced slurry surface, Lagadec et al. (2012) measured a 35% reduction in cumulative emissions (CH_4 and N_2O) with the use of manure gutters and by 55% with the use of a flushing tube, compared with having a static pit. Kroodsma et al. (1993) showed that the frequency, duration and pressure of the flushing water also impacted the efficiency of mitigation. Their results demonstrated that frequent flushing (every 1–2 h) for short periods (2 s) was more effective than prolonged (3–6 s) but less frequent flushing (every 3.5 h). The use of fresh water, as opposed to recycled water, has also been found to further reduce emissions (Kroodsma et al., 1993). This is especially the case for CH_4 because methanogenesis is rapidly initiated in the channel if a small proportion of the slurry remains in the pit after emptying. Without inoculums in the pit, CH_4 formation is low and is initiated after a few days (Sommer et al., 2007).

Accumulated manure can also be removed by scraping. The standard flat scraper system consists of a shallow slurry pit with a horizontal steel scraper under the slatted floor, allowing the manure to be removed from the building every day or several times a week (Groenestein, 1994). With this system, reductions of 15% for CO_2 emissions and of around 50% for CH_4 and N_2O emissions have been obtained under experimental conditions (Godbout et al., 2006; Lagadec et al., 2012). However under practical conditions, this technique has failed to significantly reduce CH_4 emissions (Lagadec et al., 2012).

Other systems have been developed to associate manure removal with under-slat separation of liquid/solid fractions. The V-shaped scraper system involves a channel with two inclined surfaces on each side of a central gutter. The liquid fraction runs off continuously under the force of gravity towards the gutter, and the solid fraction remaining on the inclined surfaces is frequently scraped (Godbout et al., 2006). These authors observed that, when manure was scraped every 2–3 days, although CO_2 emissions remained unchanged, CH_4 emissions reduced by 20%, in comparison with a deep-pit emptied once a week. Furthermore, Lagadec et al. (2012) demonstrated a 50% reduction in N_2O emissions in the case of a scraping frequency of between 3 and 12 times a day, compared with having a static pit. With the V-shaped conveyor belt system, urine constantly flows down in the middle of the belt under the force of gravity, and faeces are removed by the rotation of the belt (de Vries et al., 2013). Results obtained by de Vries et al. (2013) showed that this technique reduced CO_2 emissions by 47% and CH_4 emissions by 90%, but increased N_2O emissions by 250%. Overall, cumulative emissions (CO_2, CH_4 and N_2O) were lowered by 80% (de Vries et al., 2013).

Implementation of elementary frequent manure removal techniques does not seem to be associated with extra cost and could be easily applied in existing buildings. By contrast, flushing strategies (using manure gutters or flushing tubes) require major modifications to be made to existing houses. For new buildings, these systems are economically advantageous due to the reduced requirement to dig a shallow pit and the low operational costs (Guarino et al., 2003). For scraping systems, buildings costs are estimated to be higher than for traditional deep pit systems, i.e. +25 to +35% per animal place (Hamel et al., 2004; Lagadec et al., 2012). Aarnink et al. (2007) estimate the cost for new buildings to be fitted with V-shaped conveyor belts to be 10–15% lower than for traditional systems. However, applicability of these latest techniques in existing houses would appear difficult owing to the required modification of the existing manure outlets.

4.2.1.3. Other techniques. Some other original techniques have been developed to reduce GHG emissions from pig houses. Incorporation of humic acids into slurry has been shown to reduce CH_4 emissions by 34% by improving methanotrophic bacteria, but not to modify CO_2 or N_2O emissions (Shah and Kolar, 2012). The addition of quebracho tannins into slurry has also been shown to reduce CH_4 emissions by up to 95% due to the noxious effects of these compounds on methanogens. Soybean oil sprinkling and misting with essential oils have been shown to decrease CO_2 and CH_4 emissions by about 20% (Ni et al., 2008). By contrast, the addition of clay or zeolite to slurry has been shown to result in increased CH_4 emissions, as a consequence of the neutralization of the toxic effect of ammonia on methanogenic bacteria (Hansen et al., 1999; Kotsopoulos et al., 2008). The use of TiO_2-based paints and coatings has been shown to reduce CH_4 emissions by up to 27% due to the oxidative photocatalytic properties of the chemical (Costa et al., 2012). These findings would need to be confirmed in further studies and, in some cases, the underlying mechanisms require clarification.

4.2.1.4. Outside storage and slurry treatment. The release of gases during the outside storage of slurries is influenced by numerous factors. Seasonal and weather conditions, such as air temperature, relative humidity, wind speed and rainfall, modulate the production of GHGs from slurry (Lägue et al., 2004). Natural or synthetic coverings have been proposed as a means of mitigating emissions by reducing the emitting area, heating and turbulence at the slurry surface. However, some authors have reported increased emissions despite slurry cover (Loyon et al., 2006; Guarino et al., 2006; Van der Zaag et al., 2008). Several slurry treatments have been developed to facilitate the management of emissions and to mitigate their environmental impact. These slurry treatments include, among others, solid–liquid separation, biofiltration, vermifiltration and aerobic or anaerobic treatments (Godbout et al., 2003; Lägue et al., 2004; Loyon et al., 2007; Dinuccio et al., 2008; Lessard et al., 2009; Luth et al., 2011). Generally, strategies that reduce GHG emissions from slurry, preserve its energetic and agronomic values, and favour nutrient uptake for next steps are environmentally efficient. Among the numerous techniques available, anaerobic digestion of slurry with the production of a biogas rich in CO_2 and CH_4 offers an interesting opportunity to significantly reduce GHG emissions due to a lowered release of gases from manure, the production of renewable energy (electricity and heat) and the replacement of fossil fuel consumption. Adoption of an anaerobic digester in a pig farm for 100 fattening places has been estimated to offset a total of 125 t CO_2equiv. per year (Kaparaju and Rintala, 2011). The different techniques used to treat manure can be combined, and numerous modifications/adaptations have been developed. The level of GHG emissions related to these techniques depends on various parameters such as the type and the duration of treatment, the stage of the process, and the volume and the composition of the manure fraction. Thus, knowledge of the specific conditions for the treatment is essential for precise environmental assessment.

4.2.2. Bedded floor systems

Compared with slatted floor systems, bedded floor systems are usually associated with reduced CH_4 emissions, increased CO_2 emissions, hugely elevated N_2O emissions, and an overall increase in CO_2equiv. emissions (Table 7). The specific environment encountered within the litter, especially the combination of aerobic and anaerobic areas, as opposed to strictly anaerobic slurry, explains these emission factors. Nevertheless, bedded systems combine a wide range of rearing techniques that impact the level of emissions. Indeed, the litter may differ by the bedding material, the amount and frequency of application, the space allowance, the litter management and the removal strategy. These parameters influence the physico-chemical characteristics of the manure, such as density, humidity, temperature, pH and C/N ratio, all of which interact to modulate gas emission levels (Dewes, 1996; Groenestein and Van Faassen, 1996; Misselbrook and Powell, 2005).

Implementation of a bedded system is associated with low building costs due to reduced digging requirements. This technique may also be easily applicable in existing buildings with a concrete solid floor. However, the price of bedding material and the labour involved in litter management induce an increased cost, estimated to be between +5 and 10% compared with slatted floor systems (Krieter, 2002; Philippe et al., 2006b). The availability of substrates may constitute important opportunities or limitations of application, resulting in a different economic balance from area to area.

4.2.2.1. Type of substrate. Several bedding materials have been tested regarding their GHG emissions. The most frequent substrate used is straw, but sawdust, wood shavings or peat may also be used (Jeppsson, 1998; Robin et al., 1999; Nicks, 2004). Results of studies comparing straw litters and sawdust litters show that sawdust litters produce fewer CH_4 emissions but hugely greater N_2O emissions (Table 8). Table 8 shows that, overall, the CO_2equiv. emissions from these studies are higher with the use of sawdust; this is mainly due to the greater contribution of N_2O emissions. Interactions within the litter may explain these results. Indeed, the higher manure density observed with sawdust impairs the composting process, which normally increases the temperature of the manure and amount of air exchange through it (Jeppsson, 2000). Comparing different bedding types under barn conditions, Jeppsson (2000) found manure temperatures of 23.9 and 35.5 °C, respectively, with wood shavings and chopped straw. Lower temperatures favour the activity of nitrifying and denitrifying bacteria, with a higher level of N_2O production as a by-product (Sommer, 2001; Hansen et al., 2006). By contrast, CH_4 production is very heat-dependent, and lower temperatures will significantly diminish these emissions (Hansen et al., 2006). Husted (1994) found that emissions of CH_4 from dung heaps could be divided by a factor ranging from 2.7 to 10.3 when heap temperatures were decreased by 10 °C. Moreover, CH_4 production is also controlled by the rate of its transport throughout the manure and by oxidation (Conrad, 1989). If CH_4 production is reduced and the path of its spread is slow in the presence of oxygen, oxidation is likely to occur and consequently lower CH_4 emissions will be released (Hao and Larney, 2011). Thus, the oxidation of CH_4 into CO_2 could counterbalance the reduction in CO_2 production via the composting process.

4.2.2.2. Amount of substrate and frequency of application. Studies of the effect of the amount of substrate on GHG emissions have shown conflicting results, except for N_2O, for which reductions have been systematically observed with increased amounts of bedding material (Yamulki, 2006; Sommer and Moller, 2000; Guingand and Rugani, 2013; Philippe et al., 2014b). Indeed, Guingand and Rugani (2013) reported that N_2O emissions were lowered by 57% when straw supplies increased from 60 to 90 kg per fattening period. Higher aeration of the litter and/or increased temperatures may explain this finding. For CO_2 and CH_4 production, the underlying mechanisms seem unclear, since contradictions appear in the literature between authors (Jeppsson, 2000; Sommer and Moller, 2000; Yamulki, 2006; Rigolot et al., 2010; Guingand and Rugani, 2013; Philippe et al., 2014b). For instance, Jeppsson (2000) showed that an increase of 25% in straw supply was associated with increased (+72%) CO_2 emissions, while Philippe et al. (2014b) observed unchanged emissions with a straw rate ranging from 50 kg to 100 kg per fattening pig. In practice, interactions between the microbial pathways and the physico-chemical properties of the litter modulate the level of emissions with variable effects according to specific conditions. The main characteristics of manure involved in these processes are dry matter content, C/N ratio, availability of carbohydrates, aeration and temperature. Regarding CH_4, on the one hand, extra substrate may inhibit gas production because of greater aeration (Rigolot et al., 2010; Yamulki, 2006; Sommer and

Table 7
Effect of floor type (bedded or slatted floor) on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively).

	Bedded floor					Slatted floor			
	Litter type	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)
Weaned piglets									
Cabaraux et al., 2009	Straw	0.33	0.75	0.03	0.36	0.30	0.91	0.00	0.32
Cabaraux et al., 2009	Sawdust	0.43	0.52	0.32	0.54	0.34	0.86	0.01	0.36
Fattening pigs									
Robin et al., 1999	Sawdust	–	–	4.72	–	–	–	0.79	–
Ahlgrimm and Breford, 1998	Straw	–	2.74	–	–	–	6.16	–	–
Kermarrec and Robin, 2002	Sawdust	–	–	5.53	–	–	–	–	–
Philippe et al., 2007a	Straw	1.97	16.03	1.11	2.70	1.74	16.32	0.54	2.31
Philippe et al., 2007b	Straw	1.77	8.88	0.68	2.19	1.61	15.20	0.67	2.19
Gestating sows									
Philippe et al., 2011a	Straw	2.83	9.20	2.27	3.74	2.41	10.12	0.47	2.80

Table 8

Effect of the type of substrate on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively) associated with a bedded system.

	Straw-based deep litter				Sawdust-based deep litter			
	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2equiv. (kg)
Weaned piglets								
Nicks et al., 2003	0.46	1.58	0.36	0.61	0.48	0.77	1.39	0.91
Cabaraux et al., 2009	0.33	0.75	0.03	0.36	0.43	0.52	0.32	0.54
Fattening pigs								
Nicks et al., 2004	1.30	7.39	0.03	1.49	1.32	4.96	2.09	2.07

Moller, 2000). On the other hand, extra substrate may promote emissions by providing degradable carbohydrates for methanogenic bacteria (Guingand and Rugani, 2013; Philippe et al., 2014b).

The effect of the frequency of straw application has been addressed by Guingand and Rugani (2013). The authors observed increased emissions of CH_4 (+40%) and N_2O (+167%) when straw was supplied every week compared with every 2 weeks, although the total amount of straw was similar for both frequencies.

4.2.2.3. Surface area of the bedded area. Some studies have examined the impact on emissions of the surface area of the bedded area. Based on experimental data, Hassouna et al. (2005) proposed two emission factors for N_2O emissions related to animal density: 4–12% N_{ex} with less than 2 m^2 fattening pig^{-1} and 2–8% N_{ex} with more than 2 m^2 fattening pig^{-1}. With gestating sows, Philippe et al. (2010) measured a reduction in CO_2-, CH_4- and N_2O-emissions by 12, 33 and 28%, respectively, when the available bedded area was increased from 2.5 to 3.0 m^2 per animal.

4.2.2.4. Litter removal strategy. As in the case of slurry systems, manure removal strategies have been proposed to reduce pollutant emissions from bedded systems.

The height of a manure pile influences the level of GHG emissions. Under laboratory conditions, Dong et al. (2011) increased manure height from 10 to 40 cm by increasing the amount of manure from 6.6 to 22.8 kg. The authors obtained a lowering of CO_2- and N_2O-emissions by 53 and 11%, respectively, but a doubling of CH_4 emissions, resulting from an increase in anaerobic conditions. With straw-based deep litters, GHG emissions increase regularly over the course of time throughout the same fattening period, principally due to the accumulation of dejection (Philippe et al., 2007a; Philippe et al., 2010; Philippe et al., 2012a). In their study, Nicks et al. (2004) found that the rearing of three successive batches of pigs on the same litter did not increase the CO_2 and N_2O emissions from one fattening period to another, but that it did significantly increase CH_4 emissions from 3.3 to 12.7 g CH_4 pig^{-1} day^{-1} between the first and the third batch. Thus, frequent manure removal has been suggested as a means to mitigate emissions, and straw flow systems have been developed in response (Bruce, 1990). In this system, straw is supplied at the top of a sloped lying area. It travels down the slope with the aid of pig motion, is mixed with dung and then goes out of the pen into a passage from which manure is regularly scraped and removed. This kind of manure management is efficient in diminishing GHG emissions, as observed by Philippe et al. (2012a, who measured a reduction by 10, 46 and 55% for CO_2-, CH_4- and N_2O-emissions, respectively, compared with deep-litter. Overall, these authors found that CO_2equiv. emissions (including CO_2, CH_4 and N_2O) were reduced by 50%.

During the outside storage of solid manure, air temperature seems not to significantly influence the level of emissions, in contrast with wind speed or rainfall episodes (Wolter et al., 2004). Manure operations such as turning, stacking or covering impact on GHG emissions, but there have been some contradictory findings between studies (Hellmann et al., 1997; Paillat et al., 2005; Szanto et al., 2007; Jiang et al., 2013). Interlinked relationships between biological, physical and chemical factors inside the manure heap may explain these discrepancies. Whatever the storage conditions and treatment of manure, it is imperative that these conserve the energetic and agronomic value of the manure.

4.3. Nutrition

The main dietary strategy proposed for the abatement of pollutant gas emissions is the manipulation of the levels of crude protein and fibre content in the diet. Some dietary additives have also been studied for their impact on GHG emissions.

Evaluation of the cost-effectiveness of dietary manipulation is made difficult principally due to the large fluctuation in raw material prices depending on market conditions. For instance, the economic impact of the level of crude protein in the diet is greatly affected by the cost of soybean meal, on the one hand, and synthetic amino acids on the other hand. For the 2004–2008 period, Pineiro et al. (2009) found that the cost difference between reduced crude protein diet supplemented with amino acids and the standard diet fluctuated from +5 to 6€ per pig produced. Feedstuffs rich in dietary fibre are quite inexpensive since they are usually by-products of the feed, food or biofuel industries (e.g.: sugar beet pulp, wheat bran and distiller's grain). However, the price of high fibre diets greatly depends on local opportunities and the availability of such ingredients. Dietary manipulations are mitigation methods that are easy for farmers to apply and that can be adapted according to the circumstances.

4.3.1. Crude protein content

Diets reduced in crude protein content (CPC) but supplemented with amino acids have been given to pigs to match the protein supply with their growth potential and so to improve the efficiency of protein utilization, with similar zootechnical performance but with resulting reduced N excretion and NH_3 production (Philippe et al., 2011b). Thus, it has been suggested that a lower CPC could also reduce N_2O emissions, since NH_3 is the precursor of the formation of N_2O (Misselbrook et al., 1998). However, experiments have failed to corroborate this hypothesis (Table 9). Indeed, laboratory-scale experiments based on slurry samples have resulted in similar levels of N_2O emissions despite CPC being reduced by 15–20% (Clark et al., 2005; Le et al., 2009; Osada et al., 2011). Under barn conditions with fattening pigs on litter, Philippe et al. (2006a) reported a doubling of N_2O emissions (1.02 vs. 0.52 g N_2O pig^{-1} day^{-1}) with CPC reduced by 18%. It has also been assumed that a lower CPC would reduce CO_2- and CH_4-emissions due to improved nutrient utilization, but contradictory findings have also been observed for these gases (Table 9). In studies

Table 9
Effects of a reduction in dietary crude protein content (CPC) on emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalents (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively).

References	CO_2	CH_4	N_2O	CO_2equiv.	Context
Quiniou et al., 1995	+7%	–	–	–	Respiratory chambers, fattening pigs, 17.7 vs. 24.3% CPC
Atakora et al., 2002	−5%	–	–	–	Respiratory chambers, gestating sows, 14.8 vs. 19.3% CPC
Atakora et al., 2002	−7%	–	–	–	Respiratory chambers, lactating sows, 12.0 vs. 16.3% CPC
Atakora et al., 2003	NS	−60%	–	–	Respiratory chambers, non-pregnant sows, 11.% vs. 14.6% CPC
Atakora et al., 2005	NS	NS	–	–	Respiratory chambers, fattening pigs, 11.2 vs. 16.8% CPC
Atakora et al., 2011a	NS	−27%	–	–	Respiratory chambers, fattening pigs, 12.0 vs. 19.5% CPC
Atakora et al., 2011b	NS	−19%	–	–	Respiratory chambers, fattening pigs, 16.2 vs. 19.0% CPC
Clark et al., 2005	+10%	+10%	NS	+10%	Slurry samples, fattening pigs, 13.9 vs. 16.8% CPC
Velthof et al., 2005	–	−21%	–	–	Slurry samples, fattening pigs, 14.2 vs. 18.0% CPC
Le et al., 2009	NS	NS	NS	NS	Slurry samples, fattening pigs, 12.0 vs. 15.0% CPC
Osada et al., 2011	–	NS	NS	–	Slurry samples, fattening pigs, 14.5 vs. 17.0% CPC
Philippe et al., 2006a	NS	−13%	+96%	+7%	Pens with fattening pigs on straw litter, 14.4 vs. 17.6% CPC

involving respiratory chambers, most results have shown a non-significant difference in CO_2-exhalation despite a CPC reduction of up to 45% (Atakora et al., 2003, 2005, 2011a,b). Quiniou et al. (1995) measured an increase of 7% in respiratory CO_2 production with fattening pigs, while Atakora et al. (2002) noted a decreased production of 5–7% with reproductive sows. Regarding CH_4 emissions, some authors have reported reductions ranging from 13% under field conditions (Philippe et al., 2006a) to 60% in respiratory chambers (Atakora et al., 2002). Reduced VFA production with a low CPC diet could explain these results, since VFAs are precursors of CH_4 (Velthof et al., 2005). However, non-significant differences or increases in CH_4 production have also been obtained by some authors in cases of reduced CPC (Atakora et al., 2005; Clark et al., 2005; Le et al., 2009; Osada et al., 2011). Philippe et al. (2006a) reported a 7% increase in cumulative GHG emissions (including CO_2, CH_4 and N_2O) with pigs on litter consuming a reduced CPC diet. This was due to a higher contribution of N_2O despite lower CH_4 emissions.

4.3.2. Dietary fibre

Several studies have dealt with the impact of dietary fibre on GHG emissions (Table 10). It has been established that diets rich in fibre increase CH_4 production from both sources – animal and manure. Linear relationships were given in Section 2.2.1 for predicting enteric CH_4 production from ingested dietary fibre. But digestive production can also be modulated by parameters such as the botanical origin, the solubility and the fermentability of the fibre (Philippe et al., 2008). An experiment on sows fed different diets with a similar dietary fibre content but different sources of fibre showed a higher CH_4 production in cases where maize bran was incorporated compared with wheat bran (7.6 vs. 5.1 g CH_4 sow^{-1} day^{-1}; Le Goff et al., 2002b). Indeed, soluble fibres, as found in maize bran, sugar beet pulp or potato pulp, have a higher digestibility and fermentability than insoluble fibres, as found in wheat bran, pea hulls or seed residues (Jorgensen et al., 2007).

Higher CH_4 releases from slurry in cases of a fibrous diet have been reported under laboratory conditions by some authors (Clark et al., 2005; Velthof et al., 2005; Jarret et al., 2012). Jarret et al. (2012) compared CH_4 production from the slurries of fattening pigs fed a conventional diet (11% NDF) or a fibrous diet with 20% dried distiller's grain with solubles (DDGS; 14% NDF) and they obtained higher emissions (+76%) with the fibrous diet. The authors explained this result in terms of the lower digestibility of high fibre diets and thus the higher quantity of excreted OM (0.32 vs. 0.19 kg pig^{-1} day^{-1}). The B_0 of excreta, on the other hand, did not differ significantly between treatments (around 0.38 m^3 per kg OM). By contrast to these results, Clark et al. (2005) did not observe a significant difference in CH_4 emissions under in vitro conditions, whatever the fibre content. At house level, CH_4 emissions have been shown to increase by 13–52% with fibrous diets as much with a slatted floor as with a bedded floor (Philippe et al., 2009, 2012a,b, 2013; Pepple et al., 2011).

Regarding CO_2 production, conflicting results have been reported depending on the study and the source of emissions (Table 10). Schrama et al. (1998) measured a 25% lowering of CO_2 exhalation as a consequence of a reduction in pig activity. At house level, Philippe et al. (2009) observed an increase of 24% in emissions with a diet based on sugar beet pulp (48% NSP) compared with a conventional diet based on cereals (26% NSP). The reduced feed efficiency observed with a fibrous diet could explain this result.

N_2O emissions from slurry-based systems are unaffected by dietary fibre content (Clark et al., 2005; Pepple et al., 2011; Philippe et al., 2012b), in contrast to bedded systems, for which emissions have been shown to reduce with a high-fibre diet (Philippe et al., 2009, 2012b). In fact, with a fibrous diet, the pig's motivation to

Table 10
Effects of dietary fibre content on emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalents (CO_2equiv., including CO_2, CH_4 and N_2O and taking into account the global warming potential of 25 and 298 for CH_4 and N_2O, respectively).

References	CO_2	CH_4	N_2O	CO_2equiv.	Context
Schrama et al., 1998	−25%	+96%	–	–	Respiratory chambers, fattening pigs, 12 vs. 18% NSP (0 vs. 17% SBP)
Wang et al., 2004	+6%	+153%	–	–	Respiratory chambers, fattening pigs, 4 vs. 11.6% NSP (0 vs. 12% SBP)
Li et al. 2011	−7%	+93%	–	–	Environmentally controlled pens, fattening pigs, 32 vs. 40% NDF (0 vs. 20% DDGS)
Clark et al., 2005	−17%	NS	NS	−5%	Slurry samples from fattening pigs, 0 vs. 20% SBP
Velthof et al., 2005	–	+74%	–		Slurry samples from fattening pigs, 13 vs. 25% NSP
Jarret et al., 2012	–	+76%	–		Slurry samples from fattening pigs, 11 vs. 14% NDF (0 vs. 13% DDGS)
Philippe et al., 2009	+24%	+13%	−61%	+5%	Pens with gestating sows on straw litter, 26 vs. 48% NSP (7 vs. 42% SBP)
Pepple et al., 2011	−13%	+45%	NS	+28%	Buildings with fattening pigs on a slatted floor, 0 vs. 20% DDGS
Philippe et al., 2013	−9%	+33%	NS	−6%	Pen with fattening pigs on a slatted floor, 18 vs. 30% NSP (0 vs. 23% SBP)
Philippe et al., 2012b	NS	+44%	NS	+6%	Pen with gestating sows on a slatted floor, 25 vs. 44% NSP (0 vs. 37% SBP)
Philippe et al., 2012b	+14%	+52%	−40%	+9%	Pen with gestating sows on straw litter, 25 vs. 44% NSP (0 vs. 37% SBP)

NSP: non-starch polysaccharides; SBP: sugar beet pulp; NDF: neutral detergent fibre, DDGS: dried distiller's grain with solubles.

manipulate and to chew the straw is reduced, as a sign of greater satiety (Philippe et al., 2008). Thus, the litter is more aerated with longer wisps of straw, which limits N_2O production.

Overall, cumulative GHG emissions (combining CO_2, CH_4 and N_2O) seem to be little influenced by the presence of dietary fibre. This can be seen in reports by authors regarding emissions within a context of pigs receiving increased dietary fibre. Emission levels at house level ranged from −6 to +9% compared with emissions produced by pigs consuming a conventional diet (Philippe et al., 2009, 2012a,b). An exception to this finding can be seen in the study of Pepple et al. (2011), who observed that CO_2equiv. emissions increased by 28% where pigs received a high fibre diet. The authors explained this result in terms of the large contribution of CH_4 in their experimental conditions due to a long storage duration of slurries inside the building.

4.3.3. Feed additives

Several feed additives have been studied for their influence on environmental factors, especially on ammonia emissions, but few experiments have dealt with greenhouse gas emissions resulting from these additives.

Most studies have argued that feed supplementations that improve nutrient digestibility and growth performance in pigs potentially reduce pollutant gas emissions on an absolute scale and per product unit (Moehn et al., 2007). However, this statement has rarely been experimentally tested and validated.

Cellulases and hemicellulases have been added to animal diets in order to counterbalance the anti-nutritional effects of fermentable fibres and to improve animal performance (O'Shea et al., 2010). A further beneficial effect of these enzymes may be a reduction in CH_4 production by enteric bacteria, which are linearly related to fibre ingestion. However, Moehn et al. (2007) observed a tendency for increased CH_4 emissions despite xylanase supplementation.

Dietary inclusion of acidifying salts has also been suggested as a means to modify GHG production. Yet Aarnink et al. (2008) did not observe a significant difference in CH_4 and N_2O emissions despite the addition of 1% benzoic acid in the diet of fattening pigs. Eriksen et al. (2010) showed that a diet supplemented with 2% benzoic acid resulted in a transient reduction in CH_4-emissions from slurries stored under laboratory conditions (from day 20 to 34 of storage). The authors explained this result in terms of the inhibition of methanogenic bacteria, possibly due to a reduction in manure pH, the toxic effect of sulphides or the direct impact of benzoic acid. The temporality of the reduction could reflect the adaptation of the bacteria to slurry acidification.

Yucca extract inclusion has been proposed as a means to inhibit urease activity and to chemically convert or bind NH_3 (Duffy and Brooks, 1998), leading to an improvement in the performance and health status of pigs (Colina et al., 2001). However, Amon et al. (1995) measured an increase in CO_2 production with the dietary addition of *Yucca shidigera* extract. The effects on CH_4 and N_2O emissions of the inclusion of *Yucca* extract in the diet of pigs are still unknown.

The addition of phytase, primarily used to reduce phosphorus excretion, has been shown to increase feed efficiency and protein deposition, and this could possibly lead to a decrease in emissions (Ball and Möhn, 2003). However, to the best of our knowledge, the addition of phytase has not been studied for its effect on GHG emissions.

Probiotic agents are believed to improve the microbial environment in the gut, leading to better digestibility, performance and health status as a result (Fuller, 1989; Tsukahara et al., 2001). Under laboratory conditions, Tsukahara et al. (2001) measured emissions from the intestinal content of piglets fed a diet supplemented with a mixture of live lactic acid bacteria (*Lactobacillus acidophilus*,*Bifidobacterium bifidum* and *Enterococcus faecalis*). The authors obtained reductions of approximately 50 and 35% for CO_2- and CH_4-emissions, respectively, explained by the fact that lactic acid bacteria are stoichiometrically less favourable to gas production (Stanier et al., 1986). Barn experiments would need to be carried out to confirm these findings on a larger scale.

5. Conclusion

This review has reported and analysed the results of studies in the literature regarding GHG emissions produced by animals and manure in pig houses. Taking into account the results regarding CO_2-, CH_4- and N_2O-production, cumulative emissions of GHGs produced by pigs and manure at pig house level are estimated to approximately 4.87 kg CO_2equiv. per kg of carcass. Although CO_2 is the main contributor of these emissions (accounting for about 81%), this gas is usually not included in the calculation of overall GHG production because it is assumed that CO_2 emitted by livestock is compensated during photosynthesis by plants used as feed. In addition in the past, CO_2 emissions from manure were often erroneously considered negligible, while they can represent up to 40% of respiratory production.

The production levels of CO_2, as for CH_4 and N_2O, can be altered by several factors, such as housing conditions, manure management and diet composition. For instance, comparisons between slatted and bedded floor systems show higher CO_2equiv. emissions from bedded floor systems due to greater CO_2 emissions but mainly due to high N_2O emissions that are not counterbalanced by the eventual reduction in CH_4 emissions. While litter systems are usually associated with a better brand image and are commonly required for environmental labelling, the data reported in this review show that the environmental benefits are not always so obvious for all aspects of the production process. Moreover, GHG emissions from bedded systems greatly depend on the type, the amount and the frequency of substrate supply. These parameters may interact, with variable impacts, on emission levels. Further studies need to be carried out in order to understand more precisely the underlying phenomena and interactions that modulate GHG production from litter.

Whatever the floor type, frequent manure removal is an efficient means used to diminish GHG emissions from pig buildings on the condition that emissions from outside storage operations are prevented. This is particularly true for CH_4 production, which increases greatly over the course of time and in ambient temperatures. Frequent manure removal seems particularly advantageous since manure treatments can be associated with the removal. In this sense, separation of the solid and liquid fractions of the slurry provides interesting opportunities. Indeed, this separation reduces storage requirements and transportation costs, and offers more homogenous materials for land spreading, recycling or other specific treatments in order to enhance the agronomic, energetic and environmental profitability of the processes.

Regarding dietary strategies, inclusion of fibre impacts on GHG production by increasing CH_4 emissions from the digestive tract and from the manure. For gestating sows fed with a high fibre diet and kept on a straw based deep litter, concurrent reductions in N_2O emissions have been observed, resulting in a limited effect on CO_2equiv. emissions. A reduction in dietary CPC, which is well-known to reduce N excretion, has been shown to fail to limit the release of N_2O from manure. Other feeding strategies have also been used to investigate the assumption that improved nutrient utilization can lower GHG emissions. However, this statement has not been systematically proven in experiments, since diets supplemented with feed additives such as acidifying salts, *Yucca* extracts or probiotics seem ineffective in significantly reducing the intensity of GHG emissions. Nevertheless, innovative nutritional options could be examined in the future, as they appear to be efficient in reducing emissions. Recycling of the co-products from the feed-, food- or biofuel-processing industry into animal feed requires further investigation, as this could provide economical and ecological advantages due to the allocation of the cost and the impacts. Overall, feeding strategies offer the advantage of being easy to implement and quick to adapt according to the availability and cost of raw materials, which fluctuate temporally.

Good management practices that respect the physiological requirements of the animals and that promote their zootechnical potential will have beneficial consequences on performance and indirectly on the intensity of GHG emissions. In light of this, factors such as the design of the building, the regulation of bioclimatic parameters, the sanitary status of the herd and genetic selection may modulate the level of GHG production.

The choice of rearing technique is also guided by other elements, such as animal welfare, the agronomical value of manure, investment and operating costs. Specific field conditions lead to decisions in favour of mitigation techniques. Options presented in this review may contribute to a reduction in the intensity of emissions generated by pig production. However, in order to be universally efficient, these strategies would need to be integrated on a larger scale taking into account supplementary emissions associated with pre-, on- and post-farm processing, such as feed production, energy consumption, manure spreading and the transportation of animal and products.

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