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Carbon emissions inventory of farm size pig husbandry combining Manure-DNDC model and IPCC coefficient methodology

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ABSTRACT

The increasing demand for pork products has contributed to the increase in greenhouse gas emissions (GHG). Based on survey data of pig farms in Yancheng, Jiangsu Province, China, we developed a hybrid model DICPig (DNDC and IPCC combined model for pig husbandry) by combining the Manure-DNDC (denitrification and decomposition model for manure) model with the IPCC (Intergovernmental Panel on Climate Change) agricultural greenhouse gas calculation method to calculate the total GHG emissions from the pig husbandry life cycle. This hybrid model allowed the analysis of the pig husbandry carbon emissions component structure and the identification of the factors affecting the level of emissions. The results showed that CO_2 (Carbon Dioxide) emission per pig in its life cycle is about 672.27 kg CO_2-eq. In the process of pig waste disposal, the N_2O (Nitrous oxide) emitted is 1.17 kg, and the CH_4 (Methane) emitted is 1.36 kg. Pig waste disposal and feed production processes were the two most important contributors to total pig husbandry GHG emissions, accounting for 56.92% and 28.62% of the total emissions respectively. GHG emissions from pig farms could be reduced significantly by optimizing manure management measures, constructing and utilizing biogas digesters, reducing the amount of fertilizer applied to cropping, and adopting a planting-breeding combination policy.

1. Introduction

Economic development has brought about a continuous increase in pork production and demand (Waele et al., 2020; Vinholis et al., 2021). About 30% of the world's land is directly or indirectly used in livestock and poultry production activities, and pig husbandry carbon emissions account for about 9% of global emissions (Steinfeld et al., 2006; Potter et al., 2010). As a major agricultural producer, China's annual per capita pork consumption was 20.10 kg in 2018, an increase of 20.14% over 2010 (Li et al., 2018). Furthermore, the consumption of meat has increased as a result of production-consumption contradictions (Asai et al., 2018). From 2018 to 2020, the price of pork in China, which is strongly influenced by market supply and demand, the outbreak of pig diseases, policy, and environmental factors, rose very steeply (Lin et al., 2020). Human-animal relationship was discussed deeply which may influence husbandry practices, animal welfare, environment and productivity (Pol et al., 2020). However, if farmers and managers ignore the delicate balance between pig inventory and ecology, it will have a serious negative impact on human-animal relationship. Currently, scattered spatial distribution, lack of funds and technology, weak environmental awareness, and ineffective policies are the main problems of pig husbandry in China. These bring about serious problems like large amounts of resource waste, greenhouse gas emissions (GHG), and non-point source pollution.

Recently, more and more scholars are studying on carbon emissions from pig industry. This field studies often focus on carbon sources and sinks of pig husbandry in terrestrial ecosystems, factors influencing pig farming carbon emissions, precise calculation of pig industry carbon emissions, and the role of carbon footprint in relation to economic growth. Pig husbandry exists the direct and indirect GHG emissions associated with the complete pig husbandry cycle, including carbon emissions from fodder production and all other inputs/outputs of pig husbandry, including energy consumption, intestinal fermentation, and manure management, etc. (Duan et al., 2011; Mogensen et al., 2014), which reminds researchers calculate pig farming GHG emissions by accumulating carbon emissions in each pig breeding link. Some case studies about carbon emission for pig farming were reported in the Asia, Netherlands, Denmark, England, American and Germany combined with renewable production systems (Kool et al., 2009; Gerber et al., 2013). They observed that the carbon footprint for pig farming varies from 3.5

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to 5.0 kg CO_2 eq•kg^{-1} per head in large-scale or organic pig husbandry, which is smaller than the values reported for Sichuan Province, western China (5.42 kg CO_2-eq•kg^{-1} per head) (Luo et al., 2015).

Life cycle assessment (LCA) is an excellent method for studying GHG emissions from pig farming, and it has been widely applied for the analysis of agricultural and industrial production (Qi et al., 2018). The LCA method has also been utilized in pig husbandry research. Western countries have specialized LCA models to evaluate pig life cycle GHG emissions, such as GLEAM (Panagopoulos and MacLeod, 2017), CAPRI (Weiss and Leip, 2012), ULICEES (Verge et al., 2016), and Sustain Pork (Noya et al., 2016). At present, LCA pig husbandry GHG emissions research use the emission coefficient method, or a simple black box model, without analyzing the migration and transformation process of nitrogen in the whole livestock-crop-farm system. This makes it difficult to clarify the changing characteristics of GHG emissions under different environments and management strategies (Gao et al., 2014). In order to eliminate this disadvantage, we propose a hybrid model based on the emission coefficient method combined with Manure-DNDC (DeNitrification-DeComposition) (Li et al., 2012). The Manure-DNDC is a biogeochemical model, using biogeochemical methods to simulate livestock's manure GHGs emissions processes under different environments and pig farming management modes.

Our study has four aims: (1) Use the emission factor method and Manure-DNDC model to build an efficient pig life cycle GHG emissions evaluation model towards pig farming (DICPig model). (2) Use the developed hybrid model to study GHG pig husbandry emissions in Dongnan town, Yancheng city, Jiangsu Province, China. (3) Compare the simulation results between the IPCC (Intergovernmental Panel on Climate Change) emission factor method and the developed DICPig model. (4) Uncertainty and sensitivity analysis of the DICPig model.

2. Materials and methods

2.1. Manure-DNDC model

Manure-DNDC model was designed by integrating livestock management modes with the original DNDC model (Li et al., 1992) to simulate GHGs emissions mainly for livestock manure systems. Based on the DNDC model, Manure-DNDC stresses the changes in quantity and nutrient concentrations in manure during its on-farm life cycle. A system of biochemical and geochemical processes has been integrated in the model, in order to track C and N transformations across soil-crop-livestock systems (Gao et al., 2014). The sub-models of decomposition, nitrification, and denitrification calculate N turnover in both soil organic matter (SOM) and manure organic matter driven by a group of environmental factors, including temperature, moisture, pH, redox potential, and substrate concentration gradients (Li et al., 2012).

Manure-DNDC model can simulate different environments and management strategies, such as livestock type, animal stock, fodder formula, pig farming management conditions, and manure treatment strategies as input parameters. Combined with temperature and precipitation in different regions, the user can define specific pig farming scenarios and analyze N_2O, NO, CH_4 emissions processes (Foltz et al., 2019). Also, Manure-DNDC can simulate the application of livestock manure as an organic fertilizer in the farmland reuse cycle.

2.2. DICPig model for the calculation of GHGs emissions from pig husbandry

LCA generally includes four operations: establishing goals and identifying boundaries, input inventory analysis, characterization factors impact assessment, and results analysis (Kool et al., 2009; Gerber et al., 2013; Verge et al., 2016). Drawing on related research (Hu and Wang, 2010), we defined the research boundaries of the pig husbandry life cycle as "cradle" to "market gate" because it is difficult to collect data on post-trade emissions (from farm gate to dining table) of pigs. The GHG emissions considered in the life cycle inventory (LCI) of pig husbandry are (Fig. 1): (1) indirect CO_2 emissions from fodder production (pesticides, fertilizers, fuels) and direct N_2O from field applied N-fertilizer; (2) CH_4 released from pig intestinal fermentation; (3) N_2O and CH_4 emissions during manure treatment though nitrification, denitrification, and anaerobic fermentation processes; (4) indirect CO_2 emissions from pig farming energy consumption (cleaning, illumination, and refrigeration); and (5) fuel consumption for transportation (mainly diesel oil). According to the IPCC 2006 GHG emissions calculation method, the GHG emissions of one link in the life cycle is defined as the product of the input amount and its production emission factors.

2.2.1. Fodder production carbon emissions

The calculation of GHG emissions from fodder production is the most complex part of the entire pig husbandry life cycle (Tabatabaie et al., 2018). The carbon emissions are not only from fodder production processing such as crushing, milling, and agitation, but also from the crop planting period, which includes fertilizers and pesticides production, electricity consumption, and agricultural machinery usage. The GHGs involved are mainly CO_2, N_2O, and CH_4, which include direct emissions from fertilization, as well as indirect emissions from materials and energy usage during production. The general GHG emission relationship for fodder production is given by Equation (1).

$$E_{crop_i} = e_{co_2 i} \times W_{CO_2} + e_{N_2O_i} \times W_{N_2O} \tag{1}$$

where, E_{crop_i} is the GHGs emission of crop i (kg CO_2-eq) in dry farming, $e_{co_2 i}$ is crop i CO_2 emission in life cycle (kg), $e_{N_2O_i}$ is crop i N_2O emission in life cycle (kg), W_{CO_2} (kg CO_2·kg CO_2^{-1}) and W_{N_2O} (kg − N_2O·kg − CO_2^{-1}).(kg-N2O·kg-CO2-1) (kg-N2O·kg-CO2-1)(kg N_2O·kg CO_2^{-1}) are the global warming potentials of CO_2 and N_2O respectively. Detailed calculation methods and case studies of crop carbon emissions are provided in our earlier publications (Li et al., 2018).

2.2.2. Intestinal fermentation

Compared to ruminants, pigs produce only a moderate amount of methane from the intestinal fermentation process, and the amount of CH_4 emissions are calculated according to IPCC 2006 (Eggleston et al., 2006) as Equation (2):

$$E_{ef} = W_{CH_4} \times Wef \times N, \tag{2}$$

where E_{ef} is the yearly CH_4 emissions from the pigs' intestinal fermentation (kg CO_2·year^{-1}), W_{CH4} is the global warming potential of CH_4 (kg CH_4·kg CO_2^{-1}), *Wef* is the CH_4 emission coefficient of intestinal fermentation (kg CH_4·head^{-1}·year^{-1}) and *N* denotes the number of pigs (head).

2.2.3. Pig farming energy consumption

Pig farming energy consumption which includes cleaning, lighting, and cooling, is calculated using Equation (3):

$$E_{en} = Wel \times Ec + Wma \times Fc, \tag{3}$$

where E_{en} is the yearly CO_2 emission from pig farming caused by electricity consumption (kg-CO_2·year^{-1}), *Wel* and *Wma* denote the electricity consumption coefficient (kg CO_2·kWh^{-1}) and fuel (mainly diesel oil) consumption coefficient (kg CO_2·L^{-1}), respectively, and *Ec* (kWh) and *Fc* (L) denote the amount of electricity and fuel consumption, respectively.

2.2.4. Transportation

Transportation energy consumption includes transporting feed, buying piglets, and selling pigs, which is calculated by total number of miles travelled, multiplied by the average kilometer of diesel consumption (Equation (4)).

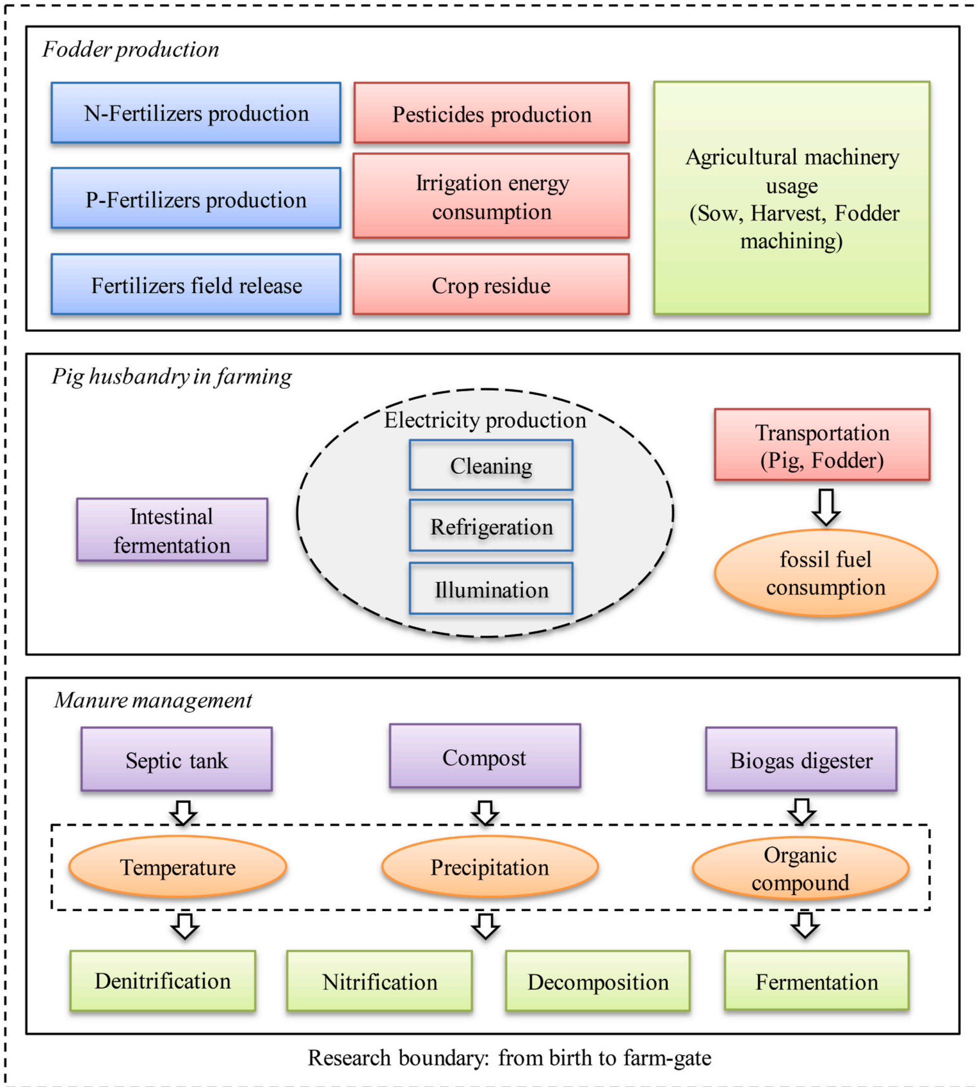

Fig. 1. The system boundary for the pig farming carbon footprint.

$$E_{tr} = Wma \times FNtr, \quad (4)$$

where E_{tr} is the yearly CO_2 emissions caused by transportation (kg $CO_2 \cdot year^{-1}$) and *Wma* denote fuel (mainly diesel oil) consumption coefficient (kg·L^{-1}). *FNtr* is the yearly amount of fuel consumed for pig husbandry (L·$year^{-1}$).

2.2.5. Manure GHG emission simulation

Manure-DNDC was chosen to simulate manure GHG emissions in pig husbandry. The inputs of Manure-DNDC include animal species, stocks, feed formula, and underlying surface of pig farming, ventilation, and climatic conditions. Manure-DNDC can simulate GHG emissions under three common management strategies for manure: composting, use of septic tanks, and use of biogas tanks (Shen et al., 2018). The clearance interval and tank volume and surface area, should be defined as input parameters in the model. The manure GHG emission is calculated by Equation (5):

$$E_{manure} = W_{N_2O} \times M_{N_2O} + W_{CH_4} \times M_{CH_4} \quad (5)$$

where M_{N_2O} is the N_2O emission simulated by the Manure-DNDC model (kg) and M_{CH_4} is the CH_4 emission simulated by Manure-DNDC model (kg). The parameter values above are shown in Table 1. W_{CH4} is the global warming potential of CH_4 (kg CH_4·kg CO_2^{-1}) and W_{N_2O} is the global warming potential of N_2O (kg N_2O·kg CO_2^{-1}).

Table 1
Parameters value of pig husbandry in the study area.

	Meaning	Unit	Value	References
W_{ef}	Intestinal fermentation coefficient	kg $CH_4 \cdot head^{-1} \cdot year^{-1}$	5.11	Kool et al. (2009)
W_{ma}	Fuel consumption coefficient	kg $CO_2 \cdot L^{-1}$	2.76	Di et al. (2007)
W_{el}	Electricity consumption coefficient	kg·CO_2·kWh^{-1}	0.94	Li et al. (2018)
W_{CO2}	The global warming potential of CO_2	kg CO_2·kg CO_2^{-1}	1	Eggleston et al. (2006)
W_{N2O}	The global warming potential of N_2O	kg CO_2·kg N_2O^{-1}	298	Eggleston et al. (2006)
W_{CH4}	The global warming potential of CH_4	kg CO_2·kg CH_4^{-1}CH4-1	25	Eggleston et al. (2006)

2.3. Data collection

Data was collected from Dongnan Town, Tinghu District, Yancheng City, Jiangsu Province, eastern China (33.49 °N , 120.43 °E) (Fig. 2).

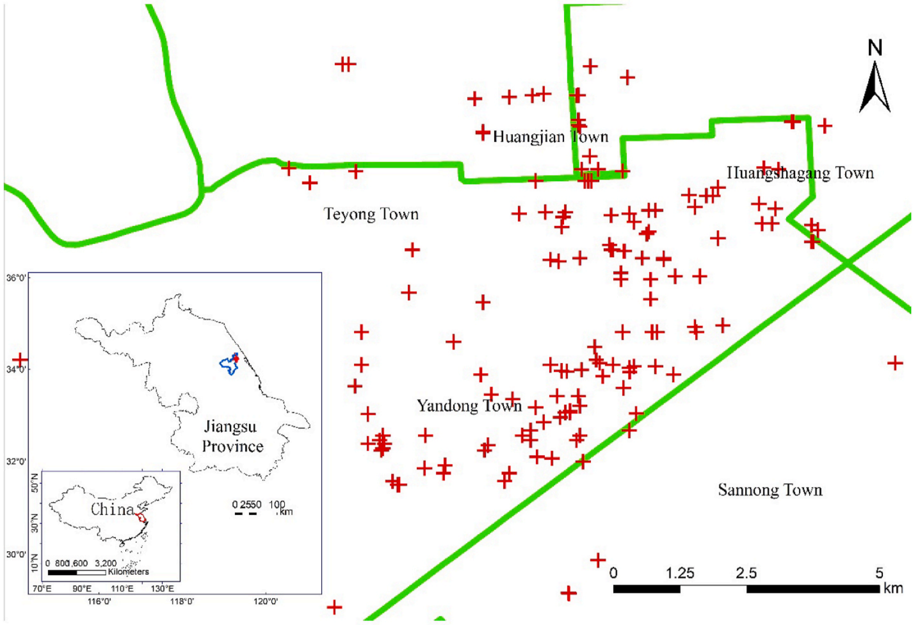

Fig. 2. Location of the study area.

This town is a famous pig husbandry town in eastern China because it's large breeding stock of pig. Field work was conducted in July 2017, and a total of 265 survey questionnaires were filled out by pig farmers who annual average breeding stock of pig greater than 150 head from the study area. As a major pig farming town in eastern China, Dongnan Town was the first to complete the pig farming transition in 2016 under the background of emphasis on the pig farming environment in China, which abandoned the stockpile manure treatment method and popularized septic tank. The cleaning system of pig farming is mostly flushing type. Waste water from cleaning pig farming flows into septic tank through pipeline. Most of septic tank in study area was uncovered to storage liquid slurry. Besides, the utilization rate of biogas digester was 24.7%, and 7.81% of farmers return manure to the field as organic fertilizer. The questionnaire information satisfied all the inputs of the DICPig model, such as pig farming scale and category, cropping-fodder production system (fertilizer, pesticides, fuel and electricity usage), pig farming management strategies and energy consumption, manure treatment, feeding formula, and fuel consumption for transportation. All input parameters of the hybrid model are shown in Table 2. Feeding formulas and input quantity for different pig ages shown in Table 3 (we didn't consider the feed differences for breeding pigs and gestation pigs). Transportation costs were calculated depended on distances between the farm and fertilized fields (Pellervo et al., 2013). The 2017 climate data including daily temperature and wind speed data came from the local meteorological station.

Table 2
Input parameters for DICPig model.

Items	Abbreviation	Values
Corn/wheat/soybean N-fertilizer ($kg{\cdot}ha^{-1}$)	-	439.28 ± 14/299.49 ± 11/159.7 ± 14.9
Corn/wheat/soybean P-fertilizer ($kg{\cdot}ha^{-1}$)	-	80.35 ± 8.3/166.64 ± 10.4/111.17 ± 11.3
Corn/wheat/soybean pesticide ($kg{\cdot}ha^{-1}$)	-	1.5 ± 0.27/1.22 ± 0.25/1.39 ± 0.37
Corn/wheat/soybean machine fuel ($L{\cdot}ha^{-1}$)	-	75.0 ± 1.0/89.25 ± 1.1/77.65 ± 3.0
Transportation fuel consumption/ $L{\cdot}year^{-1}$	FNtr	4.45 ± 0.8
Pig farming electric consumption/ $kwh{\cdot}day^{-1}$	Ec	2.54 ± 0.6
Simulation count (head)	N	6020
Pig life cycle (day)	-	160
Simulation time	-	2017 Jan.1 to Jun.9
Fodder inputs (kg)	-	1.25 ± 0.25
Manure output (kg)	-	2.5 ± 0.5
Manure treatment methods radio (Compost/septic tank/biogas tank %)	-	0/75.3/24.7%
Septic tank removal interval (day)	-	50 ± 10
Septic tank surface coverage	-	No coverage
Septic tank volume (m^3)	-	14.25 ± 3.75
Biogas tank removal interval (day)	-	60 ± 10
Biogas tank volume (m^3)	-	8
Average daily temperature (°C)	-	14.2
Average wind speed ($m{\cdot}s^{-1}$)	-	3.1

[a]Nitrogen-based fertilizers were converted to Nitrogen. [b]Phosphorus fertilizer inputs were converted to P_2O_5. [c]Pesticides were converted to active ingredients. [d]Fossil fuels (mainly diesel oil) are used for ploughing, sowing, and harvesting. [e]All data was derived from (Li et al., 2018).

2.4. Sensitivity analysis for the DICPig model

Univariate Sensitivity Index (USI) is usually used in model research to analyze the influence of input parameters changes for simulation results, and to determine the importance of each input parameter to evaluate model uncertainty (Liu et al., 2015). There are five main factors in the DICPig model: fodder input, fodder crude protein, electricity consumption, climate, and transportation fuel. These factors were analyzed by USI:

$$USI_i = \frac{f_{CF}(P_i + \Delta P_i) - M}{\Delta P_i} \times \frac{P_i}{M} \tag{6}$$

where f_{CF} is the carbon emission model function, Pi is the parameter i value input in the carbon emission model, ΔP_i is a variable value of parameter i, M is the result of pig carbon emission. P_i/M is for eliminating unit influence. These four input parameters were increased and decreased by 5%, 10%, and 15% to calculate USI. Finally, the USI value of each factor was classified and compared with other factors. The USI Grading standards are shown in Table 4.

Table 3
Feeding formulas and input quantity for different pig ages.

Age	Life cycle (day)	Daily input quantity (kg)	Feeding formula				Feed protein (%)
			Corn (%)	Soybean meal (%)	Bran (%)	Concentrated feed (%)	
Pre-weaning	1–35	0.4	60	25.5	2.5	12	19.6
After weaning to 30 kg	36–60	1.3	71.5	18	0	10.5	16.3
30 kg to slaughter	61–160	2.0	70	16	3.5	10.5	15.7

Table 4
Univariate Sensitivity Index (USI) grading standards (sensitivity was divided into four levels by USI value).

Level	USI value	Sensitivity
I	$0.00 \leq \lvert USI \rvert < 0.05$	Not sensitive
II	$0.05 \leq \lvert USI \rvert < 0.20$	Sensitive
III	$0.20 \leq \lvert USI \rvert < 1.00$	More sensitive
Ⅳ	$\lvert USI \rvert \geq 1$	The most sensitive

3. Results and analysis

3.1. Pig manure GHGs emissions simulation

Pig manure GHGs emissions from 6020 pigs were simulated from Jan.1 to Jun.9 (160 days in total) in 2017 by the DICPig model, using inputs from 74 pig farms in Dongnan. For the convenience of calculation, comparison, and discussion, the results of model simulation were averaged to a pig as a unit. In the pig husbandry life cycle, the average N_2O and CH_4 emissions per pig were 1.17 kg and 1.36 kg, respectively. According to the IPCC 2006 GHG emission calculation method, 382.66 kg of CO_2 are released in a pig life cycle. Besides total GHG emission from manure, DICPig can simulate the daily change in CH_4 and N_2O emissions (Fig. 3). During breeding time, CH_4 and N_2O emissions increased because of the increases in pig daily fodder input and manure output. During this time, more manure accumulated in septic or biogas tanks, and the resulting nitrification, denitrification, and decomposition released corresponding GHGs under these specific environments. The warming potential value of N_2O is 298, which is about 10 times more than CH_4, and thus the greenhouse contribution of N_2O is far more than CH_4 (Fig. 3) (Buckingham et al., 2014).

Temperature is an important factor affecting the decomposition rate, nitrification, denitrification, and fermentation rate of organic matter. As the pig husbandry period entered the summer, the daily average temperature was gradually increasing, and GHG emissions were also increasing, as shown in Fig. 4 and Fig. 5. Both CH_4 and N_2O emissions were significantly positively correlated with the daily average temperature. The correlation coefficient between temperature and N_2O is 0.864, and the correlation coefficient between temperature and CH_4 is higher at 0.876 (Fig. 5). Manure-DNDC divides the septic and biogas tanks into five layers according to the volume and depth of the pool. The first layer of the tank has atmospheric temperature, and the temperature values of the following layers are determined according to the attenuation coefficient of thermodynamic transmission. At the same time, Manure-DNDC distributes the organic matter to the corresponding carbon pool depending on the temperature and oxygen content, and whether the organic matter participates in nitrification, denitrification or fermentation (Deng et al., 2017). Whether it is nitrification, denitrification, decomposition, or fermentation, the CH_4 and N_2O emissions are functions of temperature. Under an aerobic environment, NH_4^+ produced by the decomposition of organic matter will be gradually oxidized to NO_2^-, and finally becoming NO_3^-. Under an anaerobic environment, the chemical reaction occurs as denitrification, with the help of anaerobic bacteria, NO3- will be restored to NO_2^- and even to NO, N_2O, N_2 (Cui and Wang, 2019). Fermentation occurs in an anaerobic environment with sufficient moisture, such as liquid uncovered septic tank lower and digester. In this environment, anaerobic microorganisms secrete hydrolytic enzymes to break down organic matter into monomolecular or monosaccharide substances, which are then broken down by methanogens to produce CH_4. Summer in eastern China is the period when carbon emissions from pig farming peak. Moreover, during summer, the most unpleasant odors from pig husbandry are released and pollution is easy to spread. So, prevention and control of carbon emission in summer is a key strategy for reducing total life cycle GHG emissions from pig husbandry.

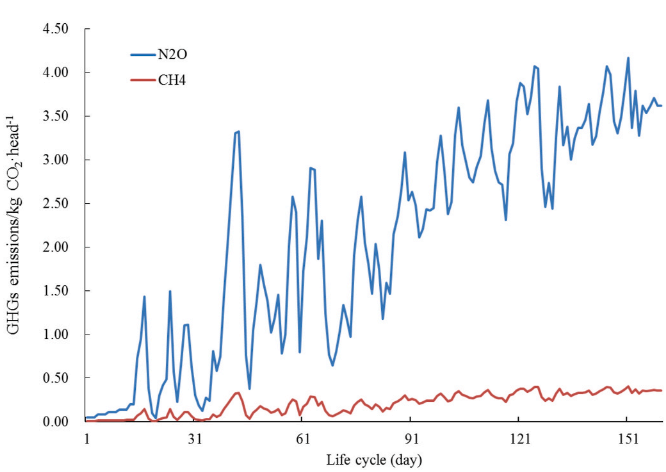

Fig. 3. GHG emissions of manure in the pig life cycle.

3.2. GHGs emissions contribution of each life cycle link

In order to determine pig husbandry GHG emissions directly and find suitable strategies for reducing GHGs emissions, we calculated GHG emissions contributions from each link in study area. As is shown in Table 5, the largest contributor to GHG emissions was manure treatment which released 382.66 kg CO_2-eq GHG emissions in total. For manure treatment, combined with the actual pig farming situation in the Dongnan Town which used septic tank to store liquid slurry as the main method of manure disposal and had low penetration rate of biogas digesters, CH_4 and N_2O were the main greenhouse gases. The N_2O emitted was 1.17 kg, and the CH_4 emitted was 1.36 kg, equaling to 348.66 kg CO_2-eq N_2O emissions and 34 kg CO_2-eq CH_4 emissions. When the septic tank storage was in liquid form as well as in the digester, it was an anaerobic water environment where the fermentation process occurs and CH_4 was the main product. Because the septic tank was uncovered, the surface layer of the septic tank was in full contact with oxygen and nitrification reactions occurred, with the end product being N_2O.

The next largest GHG emissions link in pig husbandry was fodder production which released 192.41 kg CO_2-eq GHGs emissions in total. In fodder production, GHG emissions from fertilizer had the largest contribution at 27.3%. Therefore, decreasing fertilizer usage is a key strategy for reducing GHGs emissions in the study area. The contributions of other links in the pig husbandry life cycle were relatively small. Intestinal fermentation released 64.26 kg CO_2-eq (9.56% of total GHG emissions), electricity consumption released 18.0 kg CO_2-eq (2.68% of total GHG emissions), and fuel consumption released 14.94 kg CO_2-eq

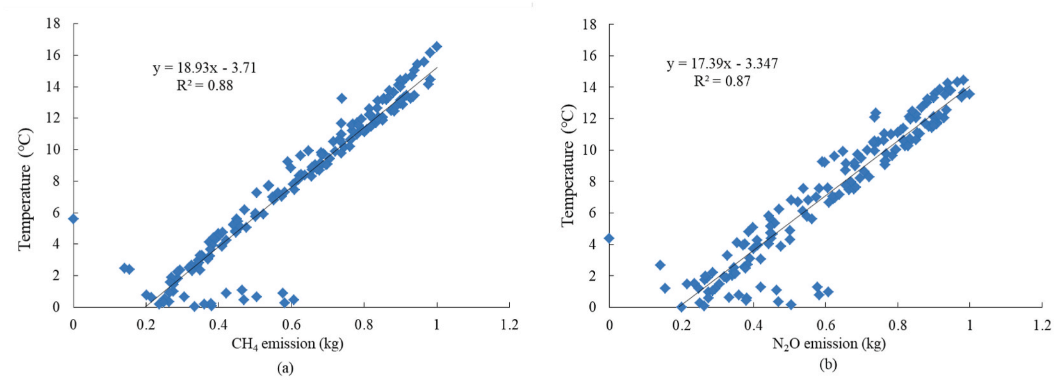

Fig. 4. Correlation relationships between CH_4, N_2O and temperature for manure treatment link; (a) was correlation relationship between CH_4 and temperature; (b) was correlation relationship between N_2O and temperature.

USI	-5%	-10%	-15%	+5%	+10%	+15%
Average temperature (℃)	0.531	0.531	0.531	0.531	0.536	0.536
Wind speed (m/s)	0.023	0.027	0.032	0.017	0.017	0.281
Fodder input (kg)	0.201	0.207	0.209	0.226	0.220	0.218
Fodder crude protein (%)	0.584	0.584	0.584	0.584	0.584	0.586
Electricity consumption (kW·h)	0.035	0.030	0.029	0.017	0.022	0.023
Transportation fuel (L)	0.030	0.026	0.024	0.013	0.017	0.019

Legend: Not sensitive: Sensitive: More sensitive:

Fig. 5. Sensitivity analysis of main input factors in DICPig model.

Table 5
GHG emissions of each link in per pig life cycle by DICPig model.

Links	Items	GHG emission (kg CO_2-eq)	Contribution radio (%)
Fodder production	Fertilizer production	63.53	9.45%
	N-Fertilizer released	120.0	17.85%
	Pesticide production	0.78	0.12%
	Machinery usage	8.10	1.21%
Intestinal fermentation	—	64.26	9.56%
Pig farming	Electricity consumption	18.0	2.68%
Transportation	Fuel consumption	14.94	2.22%
Manure treatment	N_2O emission	348.66	51.86%
	CH_4 emission	34	5.06%
Husbandry life cycle	—	672.27	100%

(2.22% of total GHG emissions).

Unlike other related LCA studies (Kool et al., 2009; Luo et al., 2015; Gerber et al., 2013), in our study, the GHG emission from manure management sector was higher than the fodder production. We believed our result was reasonable because production method differences (Luo et al., 2015) and geographical differences (Wang and Qi, 2017) may cause different carbon emission results. Our study area, Dongnan Town, just completed the industrial transformation of pig husbandry in 2017, which just achieved the use of uncovered septic tanks per household and low utilization rate of biogas tanks (24.7%). Uncovered septic tank brings the surface layer of the waste into contact with air, which results in nitrification reaction and produces N_2O emission. High value of the warming potential of N_2O greatly increases the contribution of carbon emissions from the manure treatment sector, resulting in greater carbon emissions from the manure treatment link than from the fodder production sector. According the contribution of each link to GHG emissions, we can therefor develop targeted strategies for reducing carbon emissions from pig husbandry.

3.3. Model sensitivity analysis

In order to assess the simulation accuracy of the DICPig model, the sensitivity and uncertainty of the hybrid model were analyzed by USI. A ±15% range for the main factors was used to calculate model uncertainty (Figs. 5 and 6). We selected four main factors in each pig husbandry link. Temperature affects the rate of denitrification and

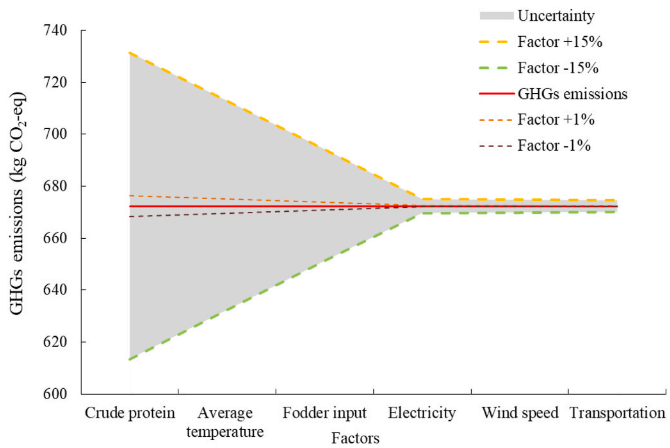

Fig. 6. Uncertainty of main input factors in DICPig model (The gray area represents the uncertainty of this factor in the DICPig model. The larger gray area represents the larger uncertainty of the corresponding factor).

decomposition and wind speed affects evaporation rate for manure skin layer GHG emissions. Fodder input and crude protein were the main input factors for the DICPig model, which were also main factors in the fodder production and manure treatment links. Electricity consumption and transportation fuel were the main factors for the pig farming and transportation links. The values of these six factors were changed by 5%, 10% and 15% in the DICPig model to analyze their sensitivities.

According to the sensitivity analysis grading standards shown in Table 3, crude protein and average temperature factors had Level III sensitivity. Fodder input factor was sensitive (Level II), and wind speed, electricity consumption and transportation fuel were not sensitive (Level I). Crude protein also had the largest uncertainty, followed by average temperature and fodder input. Wind speed, electricity consumption and transportation fuel had much lower uncertainties. Thus, the crude protein input in the Manure-DNDC model, which controlled organic matter content in pig manure, dominated the biogeochemical reaction and determined the amount of GHG emissions directly. Temperature controls the emission rate and quality of N_2O and CH_4, which can highlight the impact of environmental factors on carbon emissions from pig farming. Besides, fodder crude protein input was more sensitive factor and is one of the most important factors in both models because it's associated with direct and indirect GHGs emissions from the cropping and feed production processes.

4. Discussion

4.1. Comparison between DICPig model and emission factor method

In order to discuss the advantages of the DICPig model in pig husbandry, we calculated GHGs emissions from the case study area using the emission factor method prescribed by IPCC 2006. For emission factors in manure treatment, we used values from a study relevant to China (Hu and Wang, 2010). The N_2O emission factor was 0.53 kg $N_2O\cdot head^{-1}$ and the CH_4 emission factor value was 3.5 kg $CH_4\cdot head^{-1}$ during the whole pig life cycle. A comparison of the two models is shown in Fig. 7. The GHG emission calculated by the DICPig model was 382.66 kg CO_2-eq, which was larger than the emission factor method result (245.44 kg CO_2-eq). This is because the hybrid model considered the influence of more factors in the study area, such as climatic conditions, manure treatment methods, and manure storage conditions.

Besides the difference in total GHG emissions, the ratios of N_2O and CH_4 emissions were also different (Fig. 7). In the DICPig model, N_2O emission was 348.66 kg CO_2-eq (contribution ratio 51.86%) and CH_4 emission was 34.0 kg CO_2-eq (contribution ratio 5.06%). However in the emission factor method N_2O emission was 87.5 kg CO_2-eq (contribution ratio 16.35%) and CH_4 emission was 157.94 kg CO_2-eq (contribution ratio 29.52%). The N_2O emission calculated by the DICPig model was larger compared to the emission factor method result, but the CH_4 emission calculated by DICPig was smaller than the emission factor method result.

Though the comparison between DICPig simulation results and IPCC coefficient method listed above, the hybrid model simulation is more comprehensive for describing pig farming life cycle. First, Manure-DNDC considered more factors in the pig husbandry life cycle. Manure-DNDC is not a simple linear or experience model, but a biogeochemical process model, which includes the fodder formula system, manure treatment methods, and also considers the impact of environmental factors on GHGs emissions in manure treatment. These environmental factors, such as temperature, wind speed, cover on the tank and oxygen content, closely affect microbial activity, rate of decomposition, nitrification, denitrification and finally affect greenhouse gases species and quantity. Second, although the manure emission factor coefficients are cited from Chinese research, these coefficients are not suitable for our pig husbandry study area and can produce a large uncertainty. Third, the hybrid model simulation results were more in line with the actual pig husbandry situation in the study area. Pig farms represented by the study area in Eastern China, especially household pig farms, popularize uncovered septic tanks, had elementary waste storage and processing equipment, and low environmental awareness. These conditions caused large amounts of carbon emissions and serious non-point source pollution. Moreover, in the study area, the usage rate of septic tanks was 75.3% while the usage rate for biogas tanks was only 24.7%. So, the main manure treatment mode in the study area was uncovered septic tanks and not biogas tanks. Nitrification occurs when manure is in an uncovered septic tank, an aerobic environment, which results in N_2O released. Besides, the presence of water and isolation of oxygen in the liquid septic tank and in the digester meet the conditions for the fermentation reaction, and CH_4 is also the main GHG product.

It can be seen that using general and non-location specific emission coefficients to calculate GHG emissions will introduce uncertainties in the calculations. Compared with the emission coefficient method, using

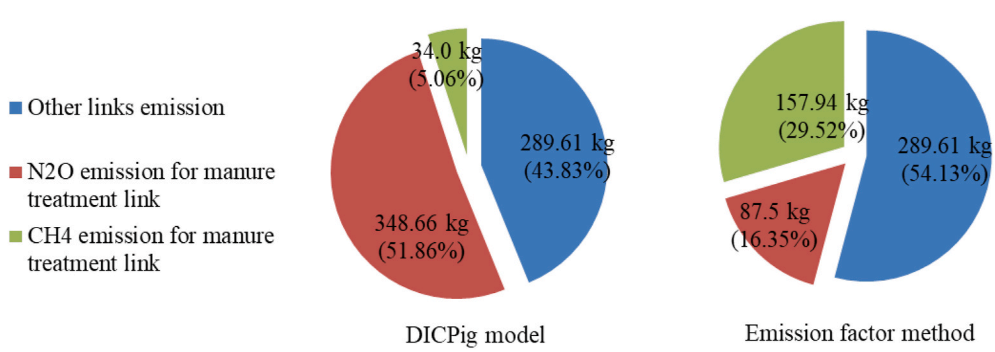

Fig. 7. Comparing the difference in the share of N_2O and CH_4 emissions for manure treatment link between the DICPig model and the IPCC coefficient method.

Manure-DNDC to construct a hybrid model (DICPig model) and simulate GHG emissions in the pig husbandry life cycle can correctly calculate the total carbon emissions of pig production activities as well as provide information on the carbon emissions structure and components through mechanism process analysis. According to the DICPig model results, the impact of environmental factors, human management factors, and even policy factors for pig husbandry can be considered. These features can significantly improve carbon emissions measurement and allow the development of regional ecological pig husbandry strategies according to local conditions.

4.2. Strategies for reducing carbon emissions

Based on the results of our study, the two-process links with the largest GHG emissions in the pig husbandry life cycle in the study area were manure treatment fodder production link, accounting for 56.92% and 28.62% of the total GHG emissions, respectively. Combined with the actual local situation, the corresponding carbon reduction strategies are proposed.

4.2.1. Strategies for manure treatment

Carbon emission from manure treatment is the largest contributor to the pig farms in case study. Therefore, reducing emissions from manure treatment should be the focus of the study area. Reducing carbon emissions from manure disposal and increasing the recycling rate of wastes are two effective ways to reduce emission from manure treatment. For pig farms in case study, compared with western large-scale pig farming, a lower quantity of live pigs cannot withstand market risks effectively. Thus, farmers do not have enough money to update waste treatment facilities. Therefore, it is necessary for the government to promote the farmers' ability to resist risks by supplying funds and services, such as increasing financial subsidies, updating equipment for enhancing manure disposal and making reasonable plans for pig husbandry. For example, a centralized disposal pattern can be used to handle wastes, which is an alternative government-based method for treating manure effectively (Basset-Mens and Werf, 2005; Cederberg et al., 2013; Dyer et al., 2010). In this method, a centralized septic tank must be established and a set of standardized manure disposal equipment can be used to reduce the GHG emissions during manure treatment link. Moreover, putting a cover on a liquid septic tank can reduce the contact between surface organic matter of the septic tank and oxygen, which prevents nitrification and reduces N_2O emissions. In the covered septic tank, meeting the conditions of both moisture and anaerobic environment, CH_4 becomes the most main GHG emission, whose warming potential value is nearly 10 times lower than that of N_2O. Thus, covered septic tanks can significantly reduce the carbon emission from the manure treatment process and reduce odour.

Planting-breeding combination is another way to reduce the carbon emissions of manure treatment link. According to the available data, the inclusion of CO_2 assimilation by plants via photosynthesis in balance sheet offsets 87.6% of the CF from the biomass consumption (Chojnacka et al., 2019). In August 2017, the Ministry of Agriculture of the People's Republic of China issued a document named *Planning and Development Program for Planting and Cycling Agricultural Demonstration Projects (2017–2020),* which provided a framework to increase the recycling rate of manure to reduce pig's carbon emission. The document suggested disposing of wastes into farmlands to improve soil quality and improve the efficiency of waste disposal. Notably, manure is the most important source of organic fertilizer for agricultural production worldwide. Manure is abundant in nutrients for crop growth such as nitrogen, phosphorus, and potassium. Applying organic fertilizer to farmlands can remarkably improve soil structure and fertility. A previous study showed that the nutrient content per ton of manure is equivalent to 20–30 kg of N-fertilizer (Pfau et al., 2017). Moreover, constructing a biogas digester is also an alternative to reduce the carbon emission of pig production. In the anaerobic environment of a biogas digester, manure is fermented by fermenting bacteria, which can produce CH_4, a clean and widely used energy source. Furthermore, a lot of heat energy is released during CH_4 production in an anaerobic environment, and that energy can be used to lower the energy consumption of pig husbandry, further reducing the carbon emission.

4.2.2. Strategies for fodder production

Excessive chemical fertilizers (mainly N-fertilizer) are added to farmlands to increase or maintain crop yields, which is the main reason for high GHGs emissions in fodder production. Large amounts of N-fertilizer applied to the soil for fodder production over a short period result in non-point pollution and other biogeochemical reactions, such as nitrification, denitrification, and fermentation (Gao et al., 2014). Developing scientific and effective methods for N-fertilizer application during agricultural production can significantly reduce the input of N-fertilizer, which will lower the emissions from pig production remarkably. In addition, long-term in-situ soil testing, slow-release nitrogen fertilizer application, and urease inhibitors can be used to increase the efficiency of N-fertilizer application and consequently reduce GHGs emissions. Otherwise, adopting a combined planting-breeding mode for fodder production and pig husbandry is an excellent method for saving breeding resources and reducing N-fertilizer usage (Kong et al., 2021).

5. Conclusions

This study combined the GHG emission calculation method prescribed by IPCC 2006 with the Manure-DNDC model to develop a new hybrid model, DICPig, to simulate GHG emissions from the pig husbandry life cycle. The new model was used to calculate the GHG emissions of the pig husbandry industry in Dongnan, China.

(1) A total of 672.27 kg CO_2-eq was released per pig life cycle by the DICpig model simulation.
(2) Using the hybrid model, the structure of GHG emissions in the study area was also analyzed. Manure treatment contributed 56.92% to the total GHG emissions, followed by fodder production with 28.62%. Intestinal fermentation, electricity consumption in pig farming, and transportation contributed 9.56%, 2.68% and 2.22%, respectively, to total GHG emissions.
(3) The sensitivity and uncertainty of the DICPig model was evaluated using univariate sensitivity analysis. Temperature, crude protein and average temperature were the two more sensitive factors in the hybrid model, and the uncertainty of the hybrid model is within a reasonable range.
(4) We compared the hybrid model and emission coefficient method results for the study area. The results verified that the DICPig model is more comprehensive to reflect the local pig farming situation compared with IPCC coefficient method.
(5) According to the pig husbandry GHGs emissions structure in the study area, strategies for reducing emissions in the pig husbandry life cycle were proposed. These strategies mainly focused on manure treatment and fodder production, including developing biogas projects, decreasing fertilizer usage, and implementing a combined planting-breeding mode.

CRediT authorship contribution statement

Qiang Li: Investigation, Writing – original draft. **Maofang Gao:** Writing – original draft, Writing – review & editing, Project administration. **Jianguo Li:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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