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Carbon accounting of pig manure management with a focus on China – discrepancies and recommendations

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Livestock manure management is a significant source of greenhouse gas (GHG) emissions in China, a leading country in pig farming. A scientific assessment of the carbon footprint of pig farming systems could provide a basis for further reducing GHG emissions in the livestock sector. This study reviewed the different GHG accounting methods for pig manure management, including Tier 2, Tier 2 Mass Flow, and Tier 3, and evaluated the impact of their implementation through a case study of an intensive pig farm. The results revealed that the emissions estimated by the IPCC Tier 2 method were 48% higher than those estimated by the Tier 2 Mass Flow method and 77% higher than those estimated by the Tier 3 process simulation-based method. Tier 2 Mass Flow and Tier 3 process modelling approaches are suggested to be more suitable for farm-level GHG emissions accounting, as the former tracks mass flow along the process and the latter incorporates regional climate conditions and microbiological activities. To enhance the accuracy and comprehensiveness of carbon accounting for China's pig farming system, it is recommended to monitor key GHG emission estimation parameters in Tier 2 Mass Flow and Tier 3 models across diverse regional farms. Furthermore, implementing these methods, which integrate farm-level accounting with regional models, could contribute to a comprehensive, bottom-up inventory of GHG emissions for manure management.

Environmental significance

Livestock manure management is a significant source of greenhouse gas (GHG) emissions in China, a leading country in pig farming. Our study makes a significant contribution to sustainability by addressing critical gaps in the accounting of GHG emissions from pig manure management. Aligned with UN SDG 13 (Climate Action), we evaluate the existing methodologies and highlight the key discrepancies using Tier 2, Tier 2 Mass Flow and Tier 3 approaches, as well as the activity data collected on-site from an intensive farm. Crucially, we identify the underlying reasons for these variations in methodology and propose a decision tree framework to support the implementation of these methods by various stakeholders. Our work supports China's ambitious carbon neutrality goals and methane reduction initiatives, providing practitioners committed to sustainable agriculture with valuable guidance.

1 Introduction

Livestock systems accounted for about 6.2 GtCO_2-eq. in 2015, equal to around 12% of total anthropogenic greenhouse gas (GHG) emissions and about 40% of total emissions from agri-food systems.[1] Manure management is an important source of GHG emissions in the livestock sector, accounting for 13% of the total emissions, with methane (CH_4) and nitrous oxide (N_2O) as significant contributors. Among the livestock in China, pork plays a significant role in the diet, contributing approximately 48% of the total environmental pressure of the livestock sector (excluding emissions from feed crop cultivation).[2] In China, the manure management sector of the large-scale pig farming contributes 5% to 43% of life cycle emissions,[3,4] which dominates the total emissions from swine production (1.68×10^3 Mt CO_2-eq.), primarily due to inefficient manure handling and large-scale operations.[5] In alignment with UN Sustainable Development Goal (SDG) 13 Climate Action, China has set ambitious targets for carbon neutrality by 2060 and has recently implemented the Methane Emission Control Action Plan. As part of this plan, China will gradually establish an accounting, reporting, and verification system for methane emissions to

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promote accurate accounting and reporting for the key emitting sources, including large livestock farms.[6]

In general, the existing GHG accounting approaches for manure management can be grouped into three categories corresponding to IPCC Tier 2, Tier 2 Mass Flow, and Tier 3 methods. Tier 2 approaches rely on aggregated activity data and emission factors based on national or regional inventories. Tier 2 Mass Flow approaches improve granularity by tracking mass and element flows across individual management stages. Tier 3 approaches, including process-based simulation models, explicitly represent biogeochemical mechanisms and environmental drivers, offering the highest resolution but at the cost of increased data and modeling requirements. Existing Tier-comparison literature has primarily focused on estimating nitrogen (N) emissions,[7] while comparative data on greenhouse gas emissions from manure management remain limited. Our previous review[3] identified significant discrepancies in the GHG emissions from manure management due to the use of various quantification approaches globally. Most studies adopted IPCC approaches and emission factors (EFs) to estimate the life cycle GHG emissions of pig farming at the regional and farm level. For example, Arrieta and González[8] estimated emissions using IPCC Tier 1 as approximately 2.6 kg CO_2-eq. per kg live weight (LW), whilst some research studies developed more refined approaches, *i.e.*, Tier 2 Mass Flow. Long, Wang, Hou, Chadwick, Ma, Cui and Zhang[9] calculated GHG emissions from the manure management as 0.46 kg CO_2-eq. per kg LW. While these results reveal that discrepancies exist in the estimation of GHG emissions, comparisons are difficult to perform due to regional factors in place, as well as the various methods used.

Thus, this study first aims to provide a comprehensive review of the state-of-the-art methodologies in GHG emissions accounting focused on manure management, highlighting the differences across varying levels of methodological granularity. Secondly, to demonstrate the effects of the choice of accounting methods on the emissions quantification, a case study based on a large-scale pig farm in China was conducted. Current guidelines of GHG accounting in Chinese livestock mainly recommend Tier 2 method at the national and regional levels.[10,11] Our findings are not only meaningful to identify hotspots, but are also expected to contribute to the guidance for bottom-up GHG emission inventory establishment for large-scale pig farming. Furthermore, the lack of accounting at the farm level hinders the implementation of efforts to reduce GHG emissions from individual emitters.[12,13] Therefore, our results can contribute to identify opportunities for GHG reduction and the establishment of a circular agricultural system in the manure management sector.[14,15]

2 Methods

2.1 Goal and scope

The expression of carbon accounting results is kg CO_2-eq. per kg LW of pig. Fig. 1 illustrates the entire chain of pig farming from feed cultivation to manure application, with the dotted box emphasizing the system boundary of the focus of this case study. It includes four main stages of manure management: indoor housing collection and storage, outdoor storage, manure treatment, and field application. Activity data were collected in 2020 from a typical intensive pig farm located in Henan Province, China, including the number of pigs, feed intake, typical animal mass, and others (SI Material Table S3).

The case farm is an intensive pig farm located in Sheqi County, Nanyang City, Henan Province (113°01′24″ E, 33°07′21″ N), with an annual slaughter of approximately 100 000 pigs. The region experiences an annual precipitation of 942.7 mm and an average temperature of 16.7 °C, typical of a warm temperate, dry climate within the northern subtropical humid monsoon zone.[16] Pigs are housed on slatted floors, with manure collected in a pit beneath the animal confinements. Manure is periodically drained, and the slurry flows to the anaerobic digestion (AD) system *via* an underground channel. The digest is stored in an anaerobic lagoon for application to the surrounding farmland, and biogas is utilized as fuel for the canteen with the remainder used for producing electricity. This study investigates GHG accounting using different tiered approaches, with the system boundary indicated in Fig. 1. The system boundary adopted in this study is consistent with that defined by the IPCC guidelines for emissions from livestock production and manure management, while the emissions related to manure resource utilization (like biogas utilization and organic fertilizer substitution, which were excluded) are quantified based on absolute emissions accounting.

2.2 Tiered approaches

Three tiered approaches were established based on IPCC Tier 2, Tier 2 Mass Flow, and Tier 3 methodologies (Table 1). Detailed calculation formulae can be found in the SI Material and the emission factors are summarized in Table 2.

2.3 Scenario analysis

2.3.1 Tier 2 methods: parameter and emission factor variations. The Tier 2 scenario analysis focused on evaluating the sensitivity of GHG emission estimates to variations in key input parameters and emission factors.

A baseline Tier 2 Mass Flow (Tier 2 MF) scenario was first established using farm-specific activity data, including the number of pigs at different growth stages, daily feed intake, and typical live weight (SI Table S3). Based on this baseline, two groups of Tier 2 scenarios were constructed.

2.3.1.1 Parameter variation scenarios. Key parameters adopted from the literature, including gross energy intake (GE), feed digestibility (DE), and average nitrogen excretion per pig (Nex), were varied to examine their impacts on CH_4 and N_2O emission estimates (SI Tables S5–S7). These parameters directly influence the manure energy content and nitrogen availability, and are therefore critical determinants of manure management GHG emissions.

2.3.1.2 Emission factor scenarios. Different emission factor (EF) sources were applied, including values from the IPCC 2019 Refinement, China's National Inventory Report (NIR) under the Tier 2 measurement, reporting and verification (MRV) framework, and the mean EF values derived from the Chinese

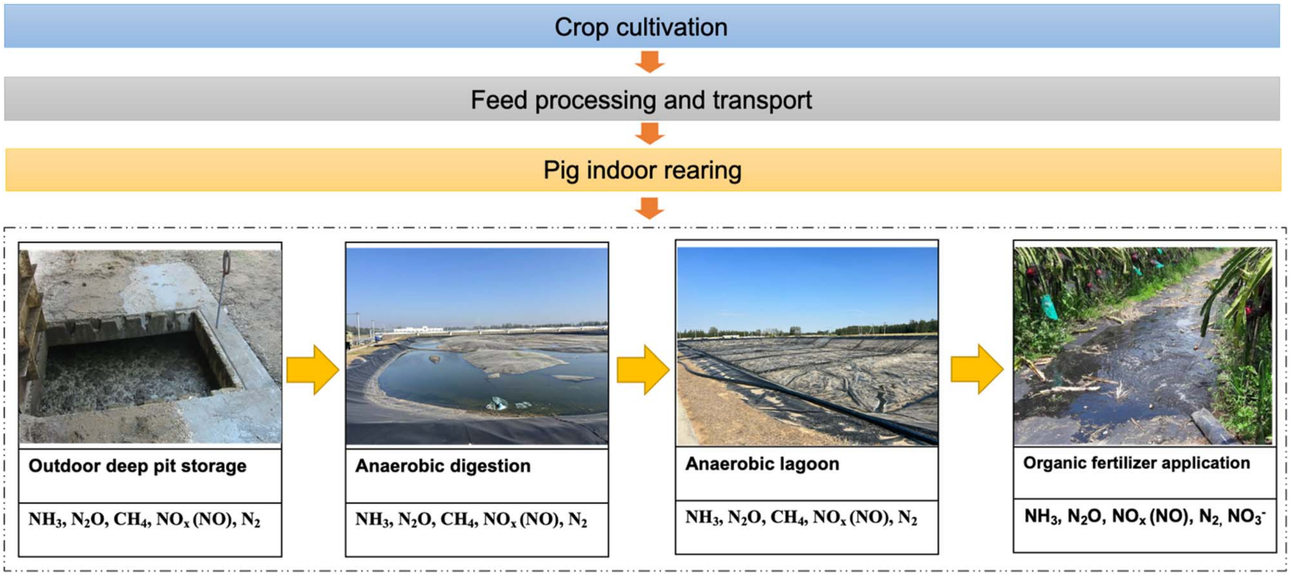

Fig. 1 System boundary of the entire supply chain in the case study. (The dashed line box signifies the processes within the system boundary of the assessment).

literature database (Table 3). All EF-based scenarios were compared against the Tier 2 MF baseline, while emission factors for other nitrogen-related pathways were kept constant.

2.3.2 Tier 3 method: site-specific climate conditions. Tier 3 scenarios were designed to evaluate the influence of regional environmental conditions on manure management GHG emissions using the process-based Manure-DNDC model. Unlike Tier 2 approaches, Tier 3 modelling dynamically simulates biogeochemical processes by incorporating site-specific inputs such as temperature, precipitation, and management conditions. To capture spatial variability, manure management was simulated for 32 different sites across China, covering longitudes from 86°02′E to 133°31′E and latitudes from 26°42′N to 47°35′N. These sites represent a wide range of climatic zones relevant to intensive pig production. Inputs for the Manure-DNDC model can be found in SI Table S4.

3 Results and discussion

To provide an overview of the recent advancements in GHG emissions accounting for manure management from life cycle perspective, this study reviewed 60 studies and analyzed their methods and outcomes. Furthermore, 328 data were utilized to demonstrate the methods at different levels of granularity regarding accounting results in Fig. 2.

Table 1 Summary of the tiered approaches

	Method	Granularity	Data requirement	Emission factors	Source/ references
Tier 2 (T2)[a]	Empirical/statistical models	National/sub-national	Medium: national statistics	Country-specific	11
Tier 2 mass-flow (T2MF)[b]	Mass balance	Farm-level	High: input/output at farm level (*e.g.*, N fertilization, yields)	Regional-specific	9
Tier 3 (T3)[c]	Process-based simulation models/ measurement	Field/farm-level	Very high: weather, soil, temperature	Dynamic	17

[a] IPCC Tier 2 (T2) calculates CH_4, direct and indirect N_2O emissions, following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.[11] [b] Tier 2 Mass-Flow (T2MF) method follows the principle of tracking C and N balance throughout manure management. The formulae used to estimate GHG emissions are adopted from Long, Wang, Hou, Chadwick, Ma, Cui and Zhang[9] (SI Material). Methane and N_2O emissions in the T2MF are determined using EFs from the 2006 IPCC guidelines,[11] as the default baseline, which is further compared with T2MF scenarios. Other nitrogen-related loss factors are based on Chinese local emission factors, as described by Long, Wang, Hou, Chadwick, Ma, Cui and Zhang.[9] [c] Tier 3 (T3) method applies the Manure-DNDC model to simulate farm-level GHG emissions based on the biogeochemical mechanism. This model, which integrates livestock management models into the original DNDC framework,[18] allows for the tracking and analysis of carbon and nitrogen transformations within soil-crop-livestock systems. It considers the direct impact of livestock activities on GHG emissions, enabling the simulation and prediction of emissions under various management practices and environmental conditions. The Manure-DNDC model factors in key elements such as the nutrient composition of feed formulae, animal stock levels, manure management practices (*e.g.*, anaerobic digestion, composting, direct land application), and methods of manure application (*e.g.*, surface spreading, subsurface injection).[17] In addition, the model has been successfully validated against field measurements in numerous studies, demonstrating strong accuracy and adaptability in simulating emissions—particularly nitrous oxide (N_2O) and ammonia (NH_3).[19–22]

Table 2 Emission factors for the Tier 2[a] and Tier 2 mass flow method[b]

Life cycle stages	Life cycle stages	NH_3–N[b] (%)	N_2O–N[a] (%)	N_2–N[b] (%)	NO–N[b] (%)	Frac (gas MS)[a]	Runoff N[b]	Leaching N[b]	Erosion N[b]	MCF CH_4[a] (%)
Indoor housing	T2		0.20%			25.00%				3.00%
	T2MF	15.00%	0.20%	5.00%	0.30%	—				3.00%
Outdoor treatment	T2		0.00%			20.00%				10.00%
	T2MF	7.00%	0.00%	5.00%	0.30%	—				10.00%
Outdoor storage	T2		0.00%			40.00%				77.00%
	T2MF	24.00%	0.00%	5.00%	0.30%	—				77.00%
Field application	T2		1.00%			20.00%				
	T2MF	20.05%	1.00%	15.00%	0.30%	—	9.60%	18.80%	0.30%	

[a] Eggleston,[11] 2006 IPCC guidelines for national greenhouse gas inventories. [b] Long, Wang, Hou, Chadwick, Ma, Cui and Zhang,[9] Mitigation of Multiple Environmental Footprints for China's Pig Production Using Different Land Use Strategies.

3.1 State-of-the-art GHG emissions accounting methods for pig manure management

To analyze the existing GHG accounting methods for pig manure management, a literature review was conducted for relevant studies published between 2010 and mid-February 2022 from four databases: Web of Science, Google Scholar, ScienceDirect, and Scopus. The keywords were ("Carbon footprint" OR "Environmental impact" OR "Environmental assessment" OR "Life cycle assessment" OR "Life cycle analysis" OR "LCA") AND (pig OR swine OR pork) in the article title, abstract, and author keywords. The screening process, flow chart and selection criteria were summarized in SI Material. A comprehensive review of accounting methods was conducted based on 60 selected studies that documented emissions inventory establishment approaches (SI Table).

Manure management involves several stages, including indoor housing collection, outdoor storage, manure treatment and field application.[9] Emissions quantification typically follows mathematical material flow analysis, where activity data are multiplied by emission factors (EF), and methods are categorized into tiered approaches, as outlined in IPCC guidelines. Tiered approaches reflect the degree of accounting complexity. This study focused on higher granularity approaches, *i.e.*, Tier 2 and Tier 3, which are country-, technology-, and conditions-specific and measurement-based methods. A heatmap was generated to visualize the accounting methods for different GHG emissions at each stage of manure management (Fig. 2). It was found that outdoor storage and field application are of more interest, followed by treatment, which is not always practiced. Among emission types, CH_4 and direct N_2O emissions are of more interest due to their importance as anthropogenic climate change drivers, followed by NH_3, which is related to the nitrogen utilization efficiency.[24]

Among these, IPCC/EMEP provides Tier 2 methods incorporating region and technology-specific emission factors, which meet most accounting requirements for CH_4 and N_2O, and are therefore widely used. For the country-level estimation of CH_4 and direct N_2O, emission factors can be derived from empirical models in terms of linear or nonlinear regressions of experimental data[25–28] or IPCC Tier 2 methodology, considering specific conditions, *e.g.*, temperature and storage time of manure.[29–31] Indirect N_2O emissions due to NH_3 and NO_x

Table 3 Emission factors for the scenario study

Life cycle stages		NH_3–N (%)	N_2O–N (%)	MCF CH_4 (%)
Indoor housing	T2MF.IPCC 2006(ref)	15.00%	0.20%	3.00%
	T2MF.IPCC 2019[a]	15.00%	0.20%	15.00%
	T2MF.NIR[b]	15.00%	0.20%	3.00%
	T2MF.Database[c]	14.36%	0.12%	—
Outdoor treatment	T2MF.IPCC 2006(ref)	7.00%	0.00%	10.00%
	T2MF.IPCC 2019[a]	7.00%	0.06%	1.00%
	T2MF.NIR[b]	7.00%	0.00%	10.00%
	T2MF.Database	2.70%	0.50%	—
Outdoor storage	T2MF.IPCC 2006(ref)	24.00%	0.00%	77.00%
	T2MF.IPCC 2019[a]	24.00%	0.00%	76.00%
	T2MF.NIR[b]	24.00%	0.00%	77.00%
	T2MF.Database	12.62%	0.48%	—
Field application	T2MF.IPCC 2006(ref)	20.05%	1.00%	—
	T2MF.IPCC 2019[a]	20.05%	0.50%	—
	T2MF.NIR[b]	20.05%	—	—
	T2MF.Database	8.54%	0.74%	—

[a] Calvo Buendia,[23] Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. [b] Dong, Zhu, Li, Wei, Zhang, Wollenberg, Wilkes, Ma, Wang, Wang, Pickering and Leahy,[10] Tier II MRV of livestock emissions in China – Final report & Annexes. [c] The mean EFs values are from the conducted Chinese database (SI Table).

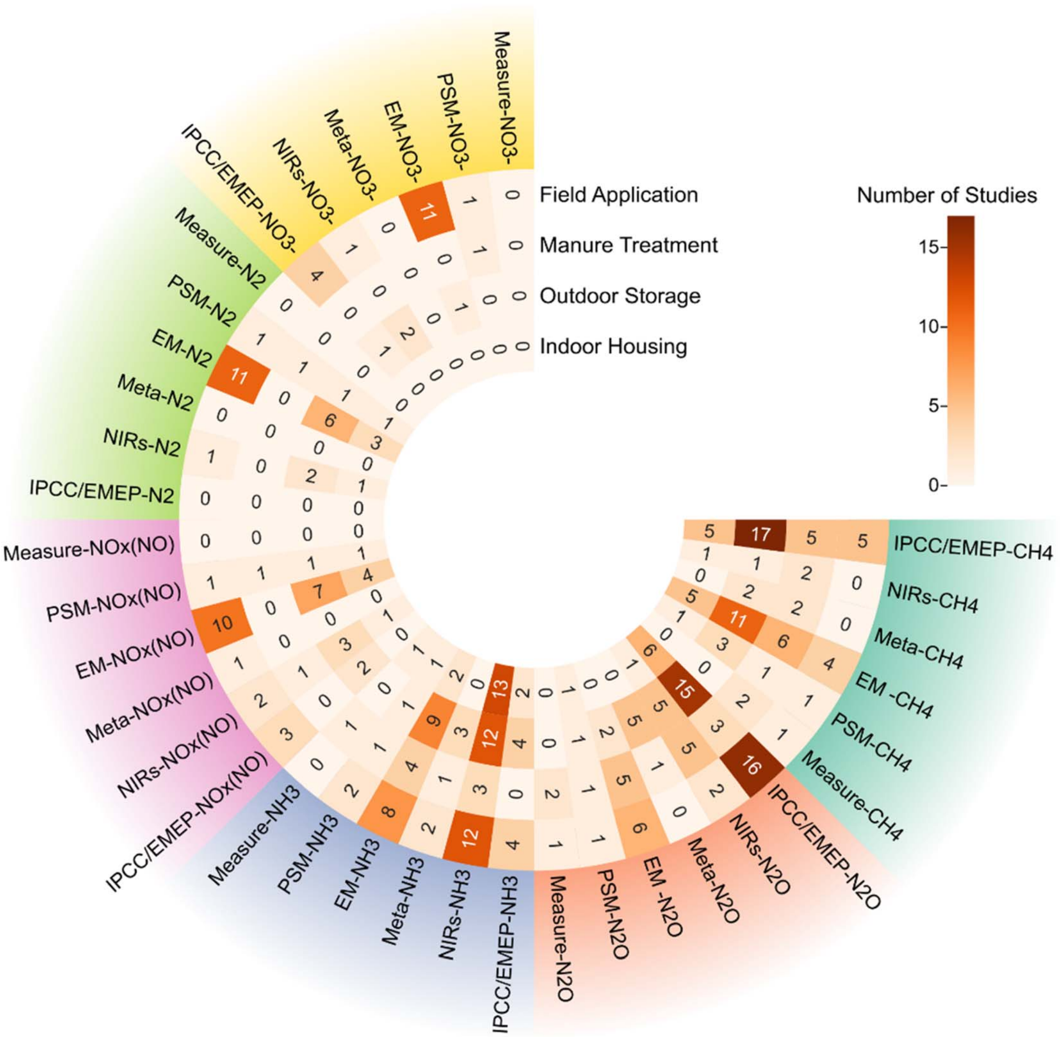

Fig. 2 Heatmap analysis of Tier 2 and Tier 3 methods for GHG and nitrogen emissions (direct N_2O, NH_3, NO_x, N_2 and NO_3^-) from manure management. IPCC/EMEP = IPCC/EMEP Guidelines; NIRs = National Gas Inventory Reports; Meta = Meta-analysis; EM = Empirical methods; PSM = Process-based simulation models.

volatilization and NO_3^- leaching are calculated mainly by multiplying IPCC default emission factors. In addition, some countries have published their own national GHG or air pollutant emission inventories, including C and N-related emissions. For example, Denmark has further developed its inventories for stationary combustion plants in order to model the combined heat and power exhaust emissions.[32]

Differing from the IPCC Tier 2 method, the Tier 2 Mass Flow method combines material flow analysis for mass balance and element tracking using emission factors. It accounts for the majority of reviewed studies ($n = 34$). For example, with regards to N-related emissions, this method accounts for emissions along N passes through the manure management and reflects the changes in the format of N (total N/mineralized N and total ammonia nitrogen/immobilized nitrogen) caused by the different manure treatment technologies. Emission factors are typically derived from four sources: (1) IPCC/the European Monitoring Environmental Programme (EMEP) Guidelines, (2) National Gas Inventory reports, (3) Empirical models, and (4) Meta-analyses. To investigate the use of emission factors in the manure management stage of swine farming in China, the emission factors with a focus on China were collected, and a dataset of emission factors from 31 Chinese articles was compiled. Details of the search terms, selection criteria and results are provided in the SI Material.

As an alternative, non-invasive field measurements (as one of the Tier 3 methods) are the most direct way to determine emissions, but require long-term monitoring through full seasons using reliable instruments.[33] These instrument-based methods include open-path Fourier transform infrared spectrometry-vertical radial plume mapping method, the sulfur hexafluoride tracer method, and the chamber method or the micrometeorological mass balance method, which is reported to be more accurate for CH_4 measurement. Gas chromatography is the main method that is used to measure N_2O. However, these measurements are expensive, and sometimes technically difficult and time-consuming.[34] Process-based simulation models, which belong to the Tier 3 method, account for climate and edaphic drivers for GHG and nitrogen emissions.[35] For example, those used in manure management include the Manure DNDC,[17] Century,[36] Roth C,[37] and Ammonia emission models,[38] which are suitable for farm-level accounting with multiple stages. The Manure DNDC model simulates biogeochemical processes such as decomposition, hydrolysis, nitrification, denitrification, and fermentation of carbon and nitrogen to estimate emissions (incl. CO_2, CH_4, N_2O, NH_3 volatilization and NO_3^- leaching) to air and water.[39] However, it currently includes only compost, lagoon or anaerobic digester facilities. Limited site information and novel manure management technologies might not be suitable for this model. Simulation models focusing on individual types of gas[40,41] have also been used to estimate ammonia and methane emissions during outdoor storage.[42–44]

For NH_3 emissions, EMEP provides Tier 2 emission factors for different manure management practices, considering factors such as climate conditions and soil pH,[45] but lacks country-specific values. National Gas Inventory Reports (NIRs), such as the national NH_3 inventories, developed by China,[46] Denmark,[47] The Netherlands,[48] the UK,[49] Ireland,[50] and Austria,[51] are used most widely. Emission factors derived *via* empirical methods are also popular data sources. As alternatives, the meta-analysis-derived emission factors for NH_3, CH_4 and N_2O are also available, and have been used to investigate the impacts of mitigation technologies.[52,53] For NO_x (mainly NO), N_2 and NO_3^-, which are normally neglected in reviewed studies due to the smaller amounts and low potential of denitrification in manure systems,[54] the estimation are generally based on the assumed ratio to direct N_2O–N emissions as $N_2O/N_2/NO = 1:3:1$ (ref. 55) and $NO/N_2O = 1:10$.[56] NO_3^-, as a minor loss of nitrogen mainly leached during field application, is calculated according to Brockmann *et al.*[57] sourced from the Smaling model,[58] or estimated as the difference between the total N input and measured nitrogen gaseous emissions.[59]

The quantification of these emissions could assist in the understanding of the fate of N and improving its utilization efficiency. Currently, NO_x and N_2 estimations still exhibit high uncertainty, especially for NO_x with a variation of up to 48.9%. This is also partly responsible for the high uncertainty for terrestrial acidification.[60] Therefore, empirical measurement of their emissions and influencing parameters in different regions is needed to build up knowledge. Once this detailed information is available, such as climatic conditions, soil and manure types, dynamic models like the soil-plant system models, Daisy[61] and N-LES,[62] can be used to systematically estimate these N losses.

3.2 Comparison of tiered approaches

The results indicated variations in GHG emission estimates when Tier 2, Tier 2 MF, and Tier 3 methods were applied to a large-scale pig farm in China, under consistent system boundaries and input data, allowing for a methodological comparison. As indicated in Fig. 3a, the GHG intensity estimated by IPCC Tier 2 methods is 3.56 kg CO_2-eq. per kg LW, which is 48% higher than that of Tier 2 Mass Flow (1.85 kg CO_2-eq. per kg LW) and 77% higher than Tier 3 (0.84 kg CO_2-eq. per kg LW). Both CH_4 and $N_2O_{indirect}$ emissions are higher in Tier 2 than in T2MF and Tier 3 methods. While N_2O_{direct} emissions are highest in the Tier 3 method at 0.45 kg CO_2-eq. per kg LW, accounting for 66% of the total GHG emissions. However, the dominance of N_2O in the Tier 3 results should be interpreted as context-dependent rather than universal, reflecting interactions among management practices, climate conditions, and soil properties.

For CH_4, the major variations in CH_4 emissions among the tiered methods come from the anaerobic lagoon (Fig. 3b). In the Tier 2 method, emissions are estimated based on activity data such as excreted volatile solid (VS) or annual average N excretion per head without considering the reduction in VS and N levels during treatments along the management chain, leading to an overestimation of GHG emissions. In addition, emission factors in Tier 2 and T2MF are based on the excreted manure, which contains more available carbon sources for methane generation, rather than treated digest after pit storage and AD. The use of these conservative emission factors overestimates the amount of methane emissions. More importantly, for CH_4 emissions from AD, the factor-based Tier 2 and T2MF methods actually estimate the methane leakage amount by a default methane conversion factor of 10%.[11] However, in this case, biogas is utilized as cooking fuel in canteens and burned to generate electricity. In large-scale biogas production systems used in Chinese intensive farming, the leakage rate was found to be 0.37% and was applied in Tier 3 accounting.[63] Furthermore, during the anaerobic lagoon stage, temperature and storage time affecting methane emissions[23] are not considered in the IPCC methane conversion factor (MCF), but are taken into account in the DNDC model.

For N_2O_{direct} emissions, large amounts of direct emissions of N_2O come from AD lagoon systems estimated by Tier 3 (Fig. 3c). Although the IPCC guidelines consider the direct N_2O emission factors from anaerobic digesters and lagoons to be zero, in reality, there are small amounts of emissions, as shown in Tier 3.[64] By applying the DNDC model, direct N_2O emissions from the field application are estimated as 0.01 kg CO_2-eq. per kg LW, lower than those from Tier 2 and T2MF methods (0.13 and 0.09 kg CO_2-eq. per kg LW, respectively).

Overall, the IPCC Tier 2 method, while region- and technology-specific in emission factors, is suitable for national or regional inventories, but fails to capture key variations in volatile solids and nitrogen content at the farm level, unlike the Tier 2 Mass Flow method. Dynamic process modeling (Tier 3) incorporates factors influencing emission, offering a more comprehensive farm-level assessment. Both T2MF and Tier 3 methods improve the accuracy of the emissions inventory, supporting sustainable practices and long-term carbon reduction strategies. The dominance of N_2O in Tier 3 results should therefore be interpreted as context-dependent rather than universal, reflecting interactions among management practices, climate conditions, and soil properties.

3.3 Scenario analysis

3.3.1 Tier 2 mass flow analysis. The impact of different sources of GE, DE and Nex on GHG emissions from manure

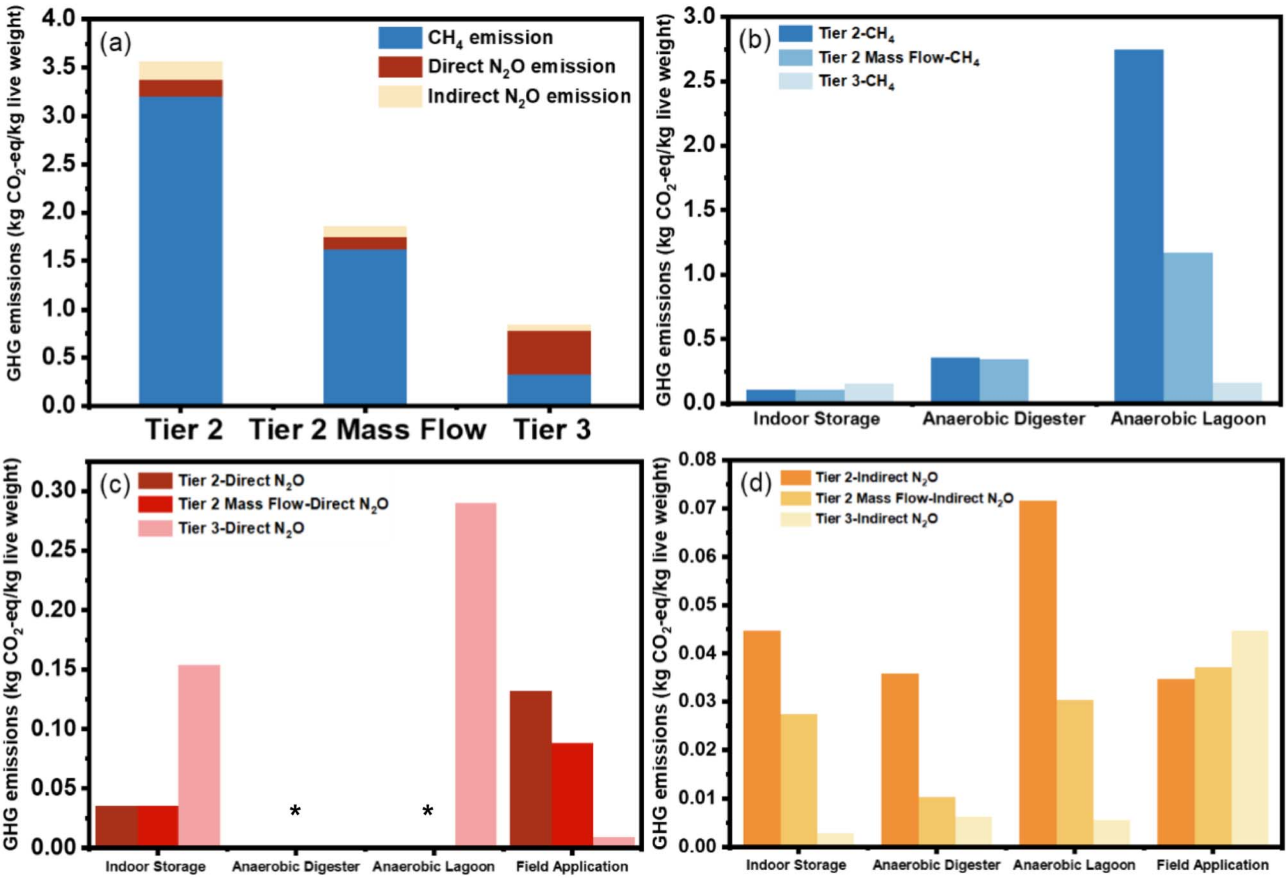

Fig. 3 Baseline GHG emissions estimated by different tiers (a) and contribution analysis (b–d).* Direct N_2O emission from anaerobic digesters and lagoons, as estimated by IPCC guidelines and T2MF, is considered to be zero.

management is relatively minor (Fig. 4). As shown in Fig. 4a, DE (digestible energy) has a more significant impact on methane emissions than GE. Both the intensive default DE (84.97% for industrial systems) and the value based on the on-site farm conditions (79.4% for nursery, 82.5% for growing-finishing, and 83.5% for sow stages) fall within the IPCC range (70–80% for mature and 80–90% for growing stages). Variations in DE can cause differences in methane emissions, typically between 1.19-2.06 kg CO_2-eq. per kg LW. Higher DE values result in lower GHG emissions. For example, using the intensive default DE overestimates the digestibility of nursery pigs, resulting in a 7% decrease in total methane emissions for the case study farm (intensive *vs.* on-site scenario, Fig. 4a DE-CH_4). Since DE is influenced by factors like feed ingredients and feed particle size,[65,66] measuring DE rather than estimating it can more accurately reflect feed characterizations and is important for the farm level GHG emissions accounting.

For methane conversion factors in the storage, those used in the NIR align with the 2006 IPCC guideline. Default MCFs for a manure management system represent the maximum level of methane production capacity for manure (B_0). This amount is affected by storage conditions, including temperature and the residence time, *etc.*.[67] The 2019 IPCC guidelines revised the MCFs, incorporating the duration of storage and conditions of climate zones. For example, the MCF for slurry in pit storage increased from 3% (2006 IPCC) to 15% (2019 IPCC), reflecting the storage for one month under a warm temperate dry climate. In the case study, where the slurry storage duration is only half a day, a 15% MCF could significantly overestimate CH_4 emissions. Given that storage time is a critical factor in CH_4 quantification, it is advisable to employ Tier 3 measurement or simulation methods, and a correlation between time and emissions should be established. For anaerobic digestion, where technologies continue to improve, including control of gas leakage and highly efficient gas-tight storage, the MCF was corrected to 1% in the 2019 IPCC Guidelines from 10% in the 2006 Guidelines. This adjustment results in a notable reduction in methane emissions, decreasing from 0.35 kg in 2006 to 0.03 kg in 2019.

For N_2O, changes in GE and Nex would also affect the emissions from manure management but only slightly and proportionally. The on-site method for calculating the total energy based on feed composition differs from the farm average method, providing a more comprehensive understanding of how feed structure influences greenhouse gas emissions in manure management (SI Table S5) when compared to simply multiplying feed dry matter intake by a default value of 18.45 MJ kg^{-1}. Moreover, using the national default Nex for sows (11.5 kg N per animal per y) may underestimate Nex (39.3 kg N per animal per y) when lactating sows consume large amounts of

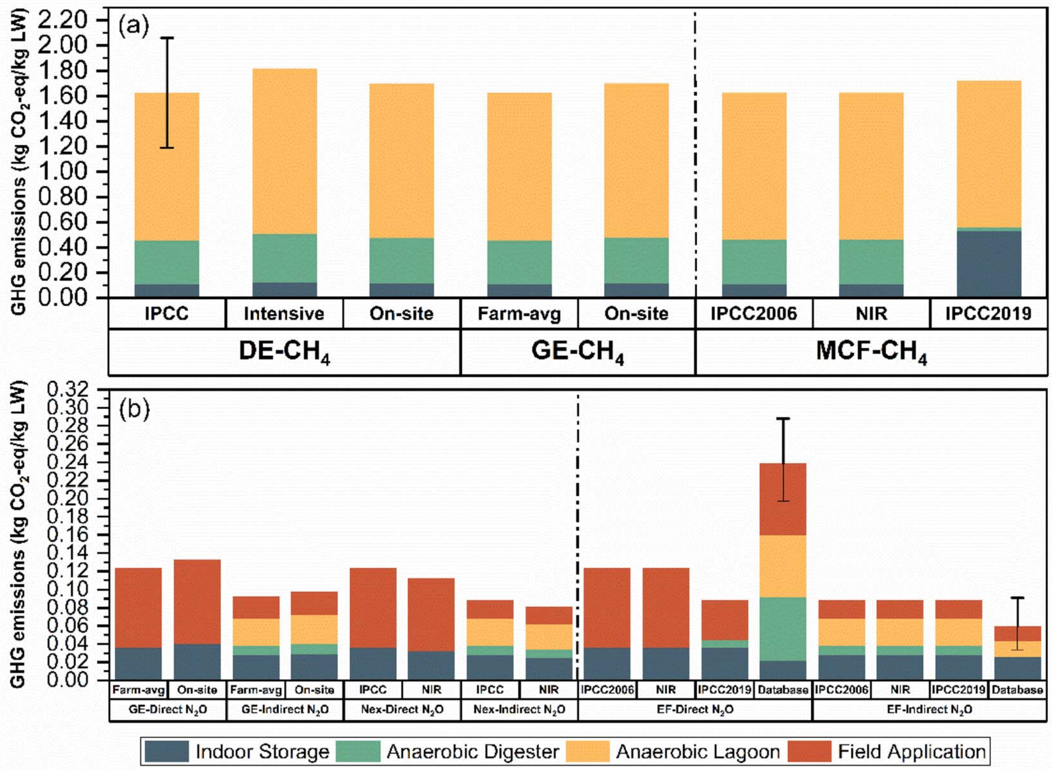

Fig. 4 Scenario analysis of methane (CH_4) (a) and nitrous oxide (N_2O) (b) estimations using different activity data and emission factors (a) error bars represent the GHG emission range calculated with different DE values as 70–80% for mature swine and 80–90% for growing swine; (b) error bars represent uncertainty from different emission factors in the EF database.

feed (SI Table S7), which will result in lower greenhouse gas emissions. Therefore, it is not advisable to rely on the national default Nex value for pig species with high feed intake.

Fig. 4b compares N_2O EFs from the 2006 and 2019 IPCC Guidelines and a self-built Chinese dataset. Given the short-term indoor storage at the farm in the case study, EFs from the Chinese database reduced the estimated direct N_2O emissions by 50%. Adopted from the 2006 IPCC Guidelines, China's NIR considers direct N_2O emissions from AD being negligible, due to the lack of oxidized forms of nitrogen entering the system and the low potential for nitrification and denitrification. However, the 2019 IPCC guidelines revised the AD EF to 0.06%, acknowledging minimal emissions during digestate storage. However, studies in China,[9,68] based on the NUFER model,[69,70] reported a higher AD emission factor of 0.5%, which examines nitrogen utilization efficiency and losses in pig farming in China, including emissions to air, groundwater, and surface water at each stage of the food chain. Direct measurements also confirm these findings, showing even greater emissions equivalent to 4.71% of total nitrogen during the digestate storage.[71] These findings highlight the importance of considering farm-specific factors to accurately estimate N_2O emissions at the farm level. For the application stage, a 0.74% emission factor from a Chinese database was applied, reflecting the farm's specific application technology and nitrogen loss in China,[72] which is more precise than the 2006 default. However, this factor does not account for climate influence, which the 2019 IPCC guidelines adjusted to 0.5% for dry climates. EF_1 represents N_2O emissions from nitrogen applications to soils. The 2006 IPCC guidelines set EF_1 at 1%, while the 2019 guidelines adjusted for climate and fertilizer type, reducing it to 0.5% in dry climates. Variations in NH_3 emissions minimally affect direct N_2O emissions but slightly reduce indirect N_2O emissions, as shown in Fig. 4b.

In summary, for key parameters, site-specific DE, GE and Nex can reflect the actual feed composition of pigs at different growth stages and are therefore more suitable for the farm-level GHG emissions accounting. Similarly, EFs that incorporating specificity in technology, site and climate conditions are more appropriate for the same purpose, and can be tailored to quantify the GHG emissions reduction from improved control measure.

3.3.2 Tier 3 analysis. Regional climate and soil conditions were extracted from 32 studies among those used to build the Chinese EF database, and were used as inputs to the DNDC model for quantifying GHG emissions across the entire manure management. It should be noted that the methane emissions reported here are those generated in AD, rather than fugitive emissions shown in Fig. 3. Therefore, across all stages, AD and housing are identified as the main contributors, accounting for 20–30% and 60–70% of total emissions, respectively. Among provinces, variations in the total GHG emissions reached up to 1.35 kg CO_2-eq. per kg LW. Results reveal that Haibei County in Qinghai Province has the lowest total GHG emissions, due to

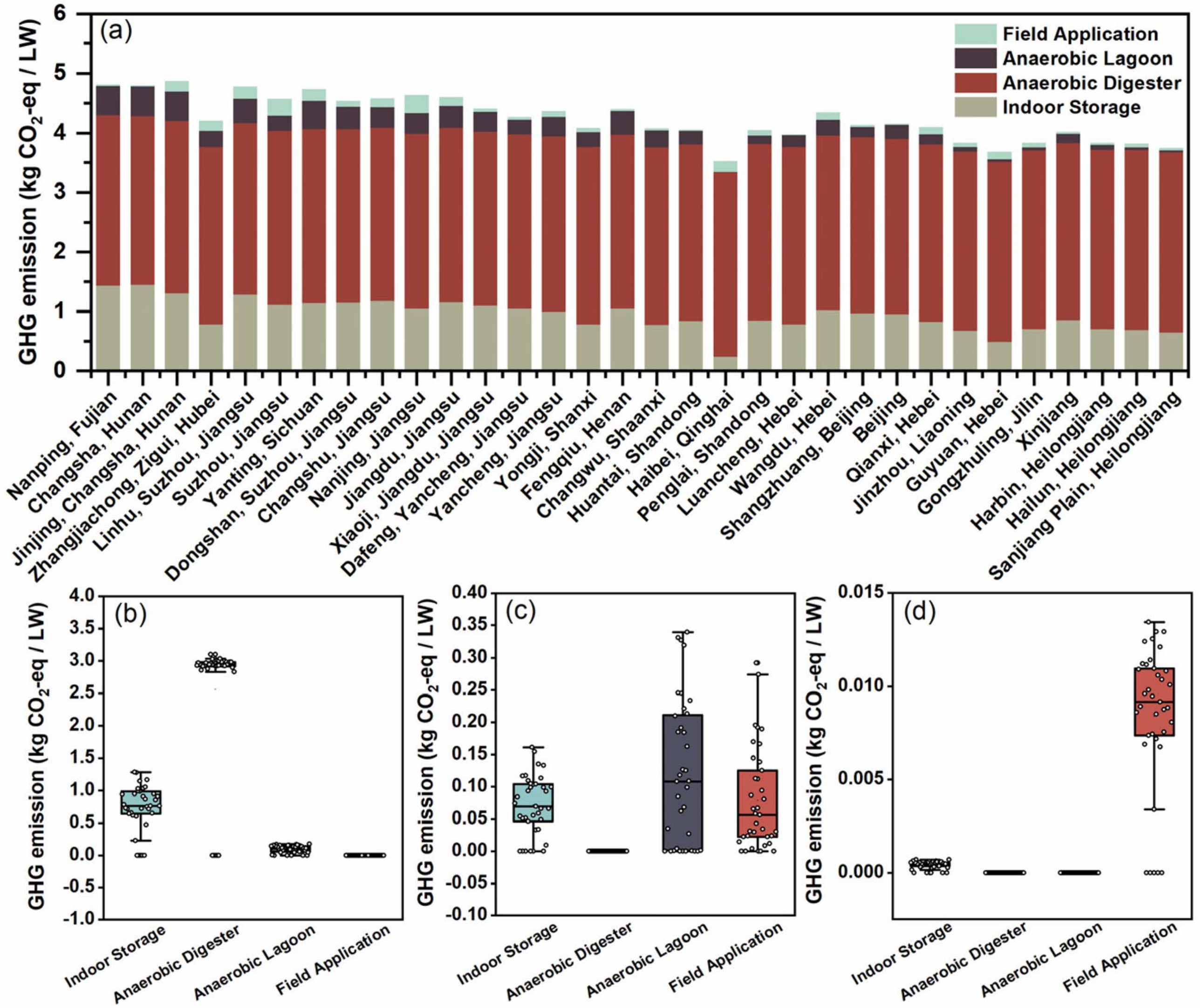

Fig. 5 GHG emissions in different provinces considering local climate and soil conditions (a) and CH_4, direct N_2O, indirect N_2O emissions by management stages (b–d, respectively).

reduced microbial activity at lower temperature in the plateau region.[73]

Classified by types of emissions and stages, results show that the CH_4 emissions from AD are the largest. In contrast, lagoon and field application are the main sources of direct N_2O, while the field application is the major contributor to indirect N_2O emissions. Variations in indirect N_2O emissions from the field application are significant due to different soil conditions and meteorological factors (Fig. 5b–d).

Climate conditions and soil texture significantly impact estimated GHG emissions, especially CH_4 and N_2O. Emissions are higher in the eastern and central southern regions under a subtropical monsoon climate, and lower in the northern and north eastern regions under a temperate continental monsoon climate. Regarding soil texture, fine-grained soils like loam and clay tend to create anaerobic conditions due to their high water retention capacity, leading to increased CH_4 emissions. On the other hand, coarse-grained soils such as sandy soils, with better aeration, result in lower total GHG emissions.[74] To further investigate the main drivers to GHG emissions, the random forest algorithm was applied to assess the relative importance of climatic and soil factors. Results reveal that temperature, soil moisture (incl. indirect effects through precipitation), and soil physical properties (*e.g.*, bulk density and soil organic carbon content) play key roles in affecting CH_4 and N_2O emissions (SI Material Fig. S3). CH_4 emissions are significantly influenced by soil organic carbon and bulk density. Bulk density affects soil aeration and the presence of anaerobic conditions, while soil organic carbon levels influence soil microbial activity and the availability of substrates for methanogens, ultimately enhancing anaerobic CH_4 production. Conversely, N_2O emissions are mainly influenced by temperature and soil moisture. Temperature plays a key role in metabolic rates, increasing respiration and subsequently reducing oxygen levels, which in turn promotes the denitrification process (Fig. 6).

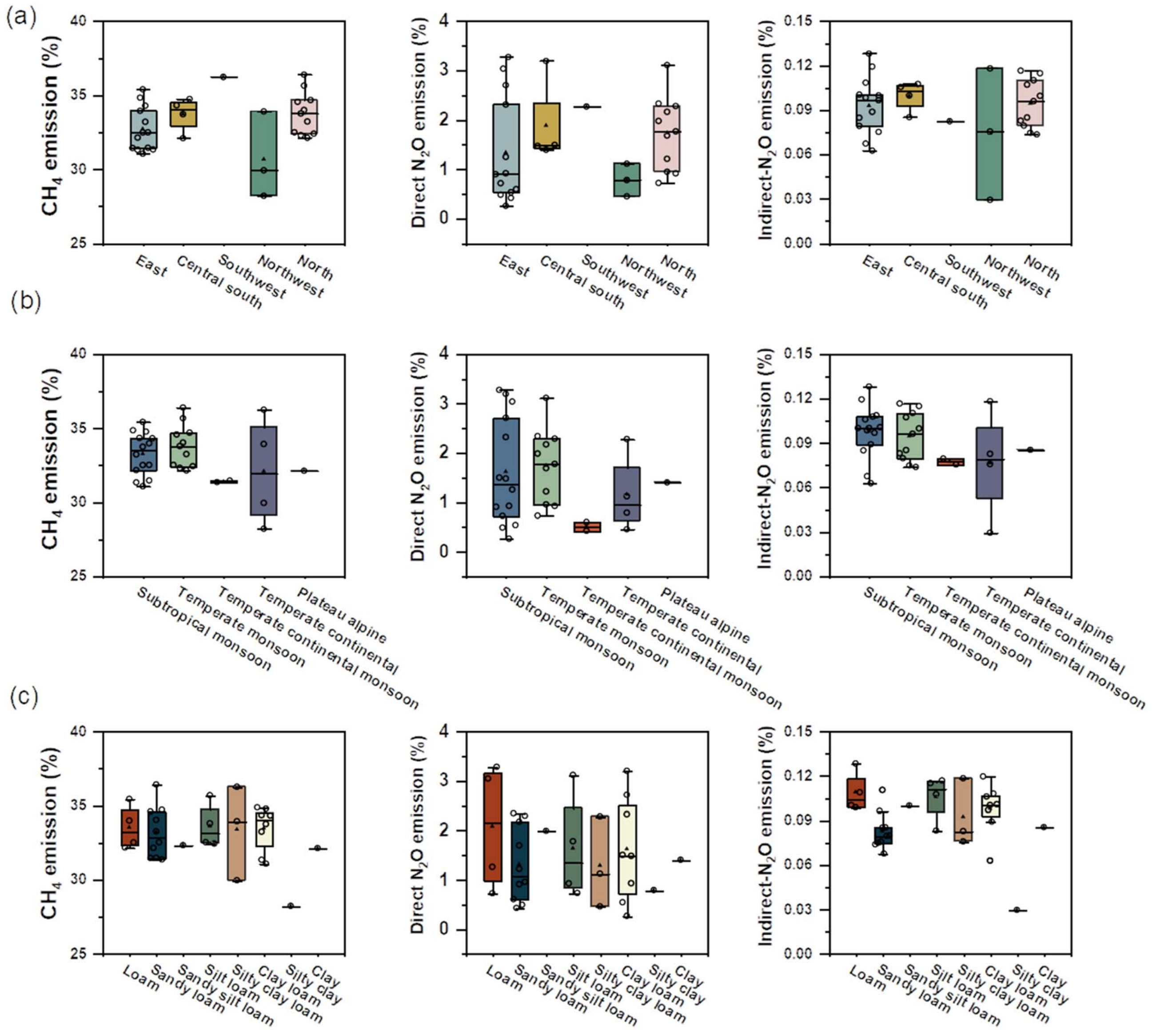

Fig. 6 CH_4, direct N_2O, and indirect N_2O emissions classified by different regions (a), climatic zones, (b) and soil types (c).

Overall, the existing GHG and N emissions accounting methods were summarised and compared using an intensive pig farm manure management as a case study. Given the variability in farm location and management practices, the numerical results from this single case study should not be extrapolated to other farms. However, the tier-comparison methodology applied here is applicable to other pig production systems. The Tier 2 Mass Flow method improves estimation accuracy over the IPCC Tier 2 method by tracking changes in C and N content along the management chain, likely resulting in lower estimated emissions. Tier 3 methods, such as the DNDC-Manure model, incorporate climate conditions and soil textures, offering more granular assessments at the farm level by accounting for biological mechanisms in manure management. Compared to the Tier 2 Mass Flow method, Tier 3 process-based modelling is dynamic, but less practical due to limitations in data sources and user customisation of the model. Based on these findings, a decision tree for accounting GHG emissions from intensive pig production and a bottom-up framework for national inventory were proposed (Fig. 7).

At the farm level, in addition to the GHG inventory estimation, Tier 2 Mass Flow allows for the assessment of the effectiveness of GHG reduction practices by reflecting the changes in the feed composition, manure characteristics, management technology improvements, and emission factors throughout the management chain. Meanwhile, Tier 3 process-based models allow for the inclusion of regional conditions. For example, a tailored field application plan for manure could be guided by the DNDC manure model by understanding the consequential effects of the application practice. As monitoring technologies continue to advance, including rapid, high-throughput and online measurement systems, the feasibility of Tier 3 approaches is expected to improve, enabling their broader application in regulatory and farm-level MRV frameworks in the

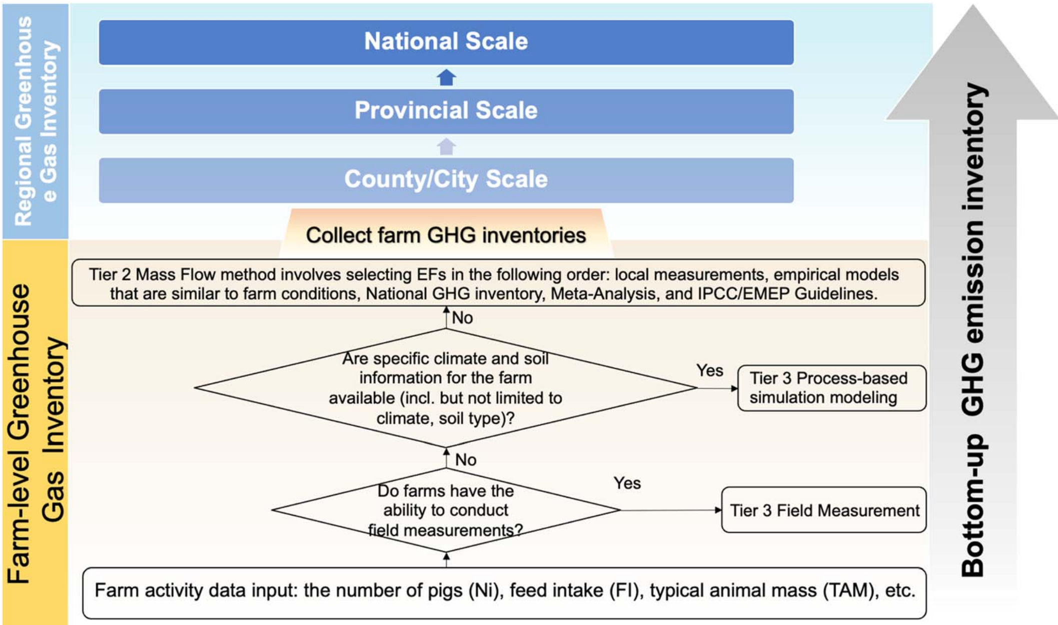

Fig. 7 Decision tree for the intensive pig farming GHG inventory and bottom-up GHG accounting framework.

future. By applying this framework, accounting results may promote improvement in the farm-scale management by altering feed, management methods, and pollutant controls, and also meet the requirements of reporting at the regional level and promoting low-carbon technologies, or adjusting the regional structure of livestock farming.

Beyond accounting methodologies, effectively reducing manure management emissions necessitates innovative approaches aimed specifically at non-CO_2 greenhouse gases. Advanced composting systems that integrate microbial inoculation and biochar amendments show promising results in enhancing emission control and nutrient conservation, making them particularly well-suited to small and medium-sized farms. Additionally, manure-derived biofertilisers promote sustainable agriculture by facilitating nutrient recycling and reducing dependency on synthetic fertilisers. Anaerobic digestion is an effective strategy for methane reduction, but its economic viability and operational efficiency depend heavily on farm size and centralized waste collection systems. Therefore, AD is more feasible for large-scale farms, whereas smaller farms may require cooperative models or modular AD units to achieve similar benefits. Comprehensive policy incentives and governmental support mechanisms are crucial in encouraging broader adoption and ensuring practical feasibility across diverse regional conditions and farm scales.

4 Conclusion

To support the development of a sustainable livestock sector in China, this study reviewed the existing GHG accounting approaches for intensive pig production and compared results in a case study. Discrepancies in CH_4 and N_2O emissions showed that the IPCC Tier 2 method significantly overestimated emissions at the farm level, with the total intensity under Tier 2 being 48% higher than the Tier 2 Mass Flow method and 77% higher than the Tier 3 method. These overestimates are mainly due to the lack of granularity of the accounting. The Tier 2 approach does not follow the loss of mass or elements in manure streams along the process chain, nor does it take into account parameters that influence the activity data and emission factors. In contrast, the Tier 3 process modelling approach considers the temperature, soil moisture and soil properties, which influence the levels of CH_4 and N_2O, *e.g.*, higher emissions in subtropical regions and fine-grained soils.

Tier 2 Mass Flow or Tier 3 methods provide more detailed accounting of C and N flows in manure management, enabling higher precision in quantification emissions from the state-of-art and alternative practices. For example, the replacement of soybean by low-protein feed or synthetic amino acids could effectively reduce excessive protein intake, and subsequently decrease the N content in manure, ammonia volatilization, and N_2O in management and field application. In addition, a decision tree is proposed to support the selection of appropriate GHG accounting methodologies at the farm and national levels, thereby facilitating evidence-based policy decisions to improve the sustainability of China's livestock sector.

Author contributions

Lei Zhang: methodology, formal analysis, investigation, data curation, writing – original draft, and visualization. Xiaoshan Hu: data curation, visualization, writing – review and editing, and resources. Xietian Zheng: data curation and visualization. Chenyuan Zhang, Qiang Liu, Zhonghao Chen, Chuan Wang, Hongwei Liu: writing – review and editing. Lei Wang: conceptualization, funding acquisition, project administration, supervision, writing – review and editing, and resources.

Conflicts of interest

The authors declare no competing interests.

Data availability

All data will be made available by the authors upon reasonable request.

Supplementary information (SI): details of the literature review, emission calculation, and scenario analysis can be found in the SI Material or Table. See DOI: https://doi.org/10.1039/d5va00248f.

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