

Toward carbon neutrality before 2060: Trajectory and technical mitigation potential of non-CO₂ greenhouse gas emissions from Chinese agriculture

Minpeng Chen^a, Yanrong Cui^a, Shan Jiang^a, Nicklas Forsell^{b,*}

^a School of Agricultural Economics and Rural Development, Renmin University of China, Beijing, 100872, PR China

^b International Institute for Applied System Analysis, Laxenburg, Austria, A-2361

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ABSTRACT

In 2020, China announced that it aims to achieve carbon neutrality before 2060. Despite the recognition of agriculture's importance in emission mitigation strategies, assessing the non-CO₂ greenhouse gas (GHG) mitigation potentials from this sector remains technically and conceptually challenging. This study developed a bottom-up inventory-based model (the Agriculture-induced non-CO₂ GreenHouse Gases InVentory model) to provide region-specific long-term projections (to 2060) of non-CO₂ GHG emissions (including methane and nitrous oxide) from the Chinese agricultural sector. Seventeen production-side technologies were identified that could reduce on-farm emissions, and their mitigation potentials by 2060 were evaluated. Results showed that agricultural non-CO₂ GHG emissions rose by 34% from 1980 to 2018, and they are projected to increase further by 33% to reach 1153 MtCO₂-eq yr⁻¹ by 2060. Implementing selected technological adaptations could lead to peak agricultural emissions before 2030 and then reduce them by 32%–50% by 2060. The most effective mitigation measures include feed supplements, feed quality improvements, slow-release fertilizers, and improved water management for paddy fields and uplands. All six regions of China will see a gradual increase in agricultural emissions. South Central China and Southwest China have the largest shares of total national emissions and the greatest mitigation potentials. However, technology adoption faces a series of socio-economic obstacles such as the high cost of technology promotion, smaller farm sizes, farmers' aversion to risk, and a complex set of objectives for agriculture.

1. Introduction

The goals set out in the Paris Agreement of limiting global warming to an increase of 2.0 °C or even 1.5 °C above pre-industrial levels entail reaching net-zero emissions of greenhouse gases (GHGs) globally before 2070 and 2050, respectively (Allen et al., 2019). However, the pledges to implement mitigation of GHG emissions, submitted to the United Nations Framework Convention on Climate Change (UNFCCC) as nationally determined contributions, fall short of the 1.5 °C goal, and will result in warming of 2.5–3.0 °C by 2100 (IPCC, 2018; Rockstrom et al., 2017; Meinshausen et al., 2022). If the net-zero emission pledges were fully implemented, global warming by the end of the 21st century would be lowered to around 2.2 °C (United Nations Environment Programme, 2021). Therefore, countries must plan for a more profound and rapid transition in all sectors to achieve the temperature goals. More than 120 countries had made net-zero pledges ahead of the UNFCCC 26th Conference of Parties held in Glasgow (United Kingdom) in 2021,

accounting for over two-thirds of the global economy (Black et al., 2021). China, the largest developing country, announced in 2020 that it aims to achieve carbon neutrality before 2060, demonstrating its determination to pursue new economic growth and development (Fu et al., 2020). In recent studies, sector pathways, national targets, and their implications across sectors have been elucidated (Duan et al., 2021; Liu et al., 2021a).

Agriculture, including crop and livestock production, is responsible for 5–7 GtCO₂-eq yr⁻¹ (approximately 10%–12%) of net anthropogenic GHG emissions globally (Frank et al., 2018; IPCC, 2020; Le Quéré et al., 2018; Rosenzweig et al., 2020). Agriculture accounted for approximately 50% of global non-CO₂ emissions in 2015, with contributions of 40%–50% and 60%–80% of total emissions of methane (CH₄) and nitrous oxide (N₂O), respectively (Ahmed et al., 2020; Frank et al., 2018; USEPA, 2019b). Globally, agricultural non-CO₂ GHG emissions have increased by 32.6% from 4.3 to 5.7 GtCO₂-eq yr⁻¹ between 1990 and 2015 (Frank et al., 2018). To feed an increasing global population,

* Corresponding author.

E-mail address: forsell@iiasa.ac.at (N. Forsell).

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global food demand is expected to increase by 60%–110% by 2050 (Suh et al., 2020). Consequently, total GHG emissions from agriculture will continue to grow at a rate of approximately 1% yr⁻¹; thus, agriculture will remain the greatest contributor of non-CO₂ GHG emissions in 2030 and even more so in 2050 (Frank et al., 2018; Roe et al., 2019). However, agriculture offers the potential for relatively low-cost mitigation opportunities (Beach et al., 2016; Gernaat et al., 2015). In order to achieve global temperature goals of 2.0 and 1.5 °C as well as carbon neutrality, a rapid and far-reaching change in global agriculture is imperative (IPCC, 2018).

Agricultural sector's profound transition will have a wide array of regional benefits and impacts. China has struggled to feed its large population as a country with almost 20% of the global population. It considers food security a top priority in its national socio-economic development strategies and plans. From 1994 to 2014, non-CO₂ GHG emissions from agricultural sources in China increased by approximately 37%, as estimated using national inventories (Fu et al., 2020). With a growing population and a general shift in dietary requirements toward more animal-based protein, non-CO₂ GHG emissions from the agricultural sector will increase in most business-as-usual (BAU) scenarios (Fu et al., 2020). Therefore, it will be a challenge for China to continue to feed its increasingly affluent population whilst simultaneously performing deep decarbonization of the agricultural sector.

Despite the recognition of agriculture's importance in global emission mitigation strategies, assessing the non-CO₂ GHG mitigation potentials from this sector remains technically and conceptually challenging. In addition to the incomplete understanding of the spatially and temporally heterogeneous processes and interdependent management practices that control the emissions, the challenge also involves the various sources of errors and uncertainties that range from inconsistent definitions, methods, and technical capacities (Beach et al., 2016; McCarl and Schneider, 2001; Tubiello et al., 2013). Several studies have assessed the mitigation potentials in agriculture using sector-specific or technology-specific bottom-up models (Ahmed et al., 2020; Beach et al., 2016; Henderson et al., 2015), or top-down models that represent economic agents in an aggregated fashion (Frank et al., 2018, 2019; Gernaat et al., 2015; Havlik et al., 2014). In contrast with other sectors, such as energy, transport, industry, and land-use, there is little knowledge regarding feasible long-term projections and sustainable mitigation strategies for reducing non-CO₂ GHG emissions from agricultural in China. Current assessments of China's agricultural industry focus either on the modeling methods used to improve emission estimates (Yue et al., 2019; Zhang et al., 2015), technical abatement potentials of specific mitigation measures (Yang et al., 2019; Zhang et al., 2019), and specific subsectors (Wang et al., 2015; Wang et al., 2017), or on specific types of food (such as staple foods) (Xia et al., 2016). Using a bottom-up marginal abatement cost curve, Wang et al. (2014b) estimated the economic potentials for 2020, but they failed to provide robust knowledge to help guide decision-making regarding 2060 goals. Therefore, a considerable knowledge gap remains with regards to exploring the implications of China's political commitments to carbon neutrality before 2060.

Utilizing national activity data and the IPCC inventory methodology, this study provides a region-specific long-term (1980–2060) projection of China's agricultural sector's non-CO₂ GHG emissions. Using a bottom-up approach, the study estimates the technical feasibility of mitigation in China's agricultural sector. This paper estimates, for the first time, the maximum technical mitigation potential and the remaining non-CO₂ GHG emissions from China's agricultural scenario for Chinese agriculture to achieve the objective of carbon neutrality before 2060.

2. Methods and data

2.1. Conceptual framework

In Fig. 1, the conceptual framework of this study is being illustrated, the core of which is an inventory-based model called the Agriculture-

induced non-CO₂ **GHG IN**ventory model (AGHG-INV) (Fu et al., 2020). As part of the study, three scenarios were developed to present possible long-term emissions trajectories: a baseline scenario (BAU), a technical mitigation scenario (TP), and a maximum technical mitigation scenario (MTP).

2.2. Inventory-based model for non-CO₂ GHG emissions from China's agricultural sector

The AGHG-INV model is a bottom-up model that incorporates technology details. It can provide non-CO₂ GHG emissions from agricultural sources at the provincial level. This model is built upon publicly available activity data from China's national statistical database (National Bureau of Statistics, 2022) and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

Primary non-CO₂ GHG sources in AGHG-INV include enteric fermentation, rice cultivation, agricultural soils, and combustion of agricultural residues. The primary method used to estimate the annual N₂O and CH₄ emissions in AGHG-INV follows the IPCC Tier 1 and Tier 2 approach.¹ The yearly emission (*Em*) of type *g* non-CO₂ GHG from emission source *s* in year *y* is calculated as follows:

$$Em_{g,s,y} = \sum_p EF_{g,p,r,s,y} \times ACT_{g,p,r,s,y} \quad (1)$$

where *ACT* is the activity level of the emission source (head, ha, kg), and *EF* is the emission factor of the emission source in process *p* in region *r* (kg head⁻¹ yr⁻¹, kg ha⁻¹, %).

Activity data, such as sown areas of major crops, number in stocks of major animals, and chemical fertilizer applications, were collected from the China Rural Statistical Yearbooks, China Compendium of Statistics 1949–2008 (National Bureau of Statistics NBS, 2008), and the National Data platform (National Bureau of Statistics NBS, 2021) (see Supplementary Information (SI) for detailed information about the data sources being applied). Crops includes rice, wheat, maize, soybean, tubes, oil crops, and cotton. Livestock includes ruminants such as cattle, dairy cattle, sheep, goats, and non-ruminant animals such as pigs, poultry, horses, asses and mules, and camels. Considering the differences in seasonal births and life spans, AGHG-INV used the average head of livestock to estimate the total emissions from enteric fermentation and manure management. For CH₄ emissions from rice cultivation, this study collected provincial-level data on cultivation areas for early rice, middle rice, and late rice.

The selection of emission factors (EFs) in AGHG-INV followed the methodology recommended in the IPCC 2006 guidelines as closely as the available data allowed (IPCC, 2006). Regional EFs were adopted for rice cultivation and manure management from the 2005 People's Republic of China National Greenhouse Gas Inventory (Government of China, 2016). Tables S1–S6 in the Supplementary Information (SI) list the reported mean, minimum, and maximum values for all EFs. All emissions were converted to CO₂ equivalent using the Global Warming Potentials (GWP₁₀₀) from the IPCC Fifth Assessment Report (AR5) as 28 times that of CO₂ for CH₄ and 265 times that of CO₂ for N₂O (IPCC, 2014). The use of AR5 GWP values rather than IPCC Sixth Assessment Report (AR6) values (IPCC, 2022) ensures compatibility with China's current climate policy environment (Meinshausen and Nicholls, 2022) and comparability with official national data, such as the China National Greenhouse Gas Inventory. Furthermore the Paris Rulebook specifies that "Each Party shall use the 100-year time horizon global warming potential (GWP) values from the IPCC Fifth Assessment Report, or 100-year time-horizon GWP values from a subsequent IPCC assessment report as

¹ A tier represents a level of methodological complexity used to estimate an outcome. Tier 1 is the basic method, Tier 2 intermediate, and Tier 3 the most demanding in terms of complexity and data requirements.

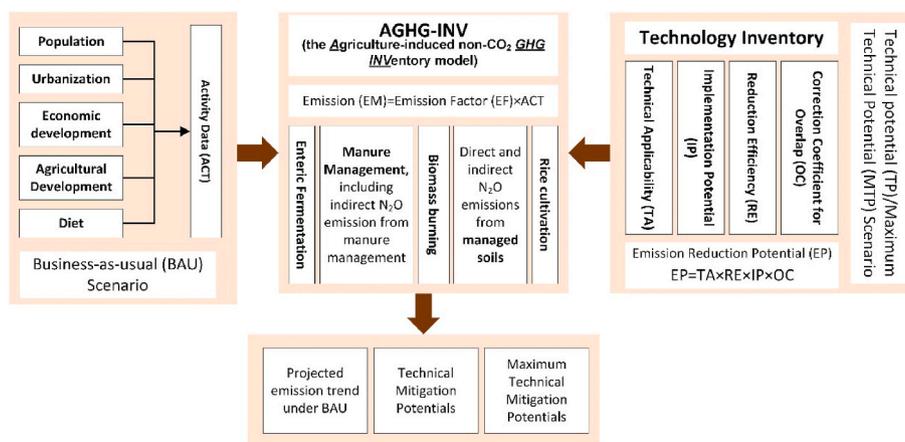


Fig. 1. Conceptual framework of model and scenario analysis.

agreed upon by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA), to report aggregate emissions and removals of GHGs, expressed in CO₂-eq.” (UNFCCC, 2019). As long as AR6 GWP values have not been adopted by the COP, AR5 GWP values will be used in all GHG inventories reported to UNFCCC. Section 3.1, however, explores the implications and effects of this choice.

2.3. Scenario analysis

2.3.1. Business-as-usual scenario

The BAU scenario includes assumptions about demographic changes, economic growth, and changes in dietary patterns. In AGHG-INVENTORY, the activity drivers for emission projections enter calculations externally using scenario data from different internationally and nationally recognized sources as listed in Table 1. Under the BAU scenario, the projected level of agricultural activity was tied to changes in the population size, urbanization, economic development, and per capita diet. The production efficiency, EFs and technology of China’s agricultural sector remain constant over time without considering further development and diffusion of mitigation policies or technologies.

Population and urbanization were from World Population Prospect (2019) and World Urbanization Prospect 2018 (UN Department of Economic and Social Affairs, 2021a,b). Population increases along the averaged pathway of the nine scenarios in the prospect, and the urbanization rates from 2051 to 2060 were obtained by applying Vector Autogression model (VAR) (Lütkepohl, 2005).

The economic development followed the average pathway by Organisation for Economic Cooperation and Development OECD (2021a), the World Bank (2021), and International Monetary Fund IMF (2021). As all available outlooks only project the economy into 2030,

the projection from 2031 to 2060 were obtained by applying VAR to extrapolate the trend from 1980 to 2030.

Concerning diet, the BAU scenario assumed that per capita dietary composition and caloric consumption continue to change as the country becomes more affluent, and that the relationship between production and consumption remains constant. Six animal-based products, including beef, pork, mutton, poultry meat, milk and egg, were estimated by four models, including ordinary least squares (OLS) regression, VAR, a simple extrapolation function based on per capital GDP, and OECD-FAO model (Organisation for Economic Cooperation and Development OECD, 2021b). The BAU scenario used the average values of the four models. The domestic livestock production were extrapolated from the historic relationship between livestock production and consumption into future, which were calibrated with the estimated into 2030 from China Agricultural Monitoring and Early-warning System (CAMES) (Committee for Market Warning, Ministry of Agriculture and Rural Development, 2021).

In terms of agricultural development, it is assumed that crop yields at the provincial level change along recent trajectories from 1980 to 2018, and a forecast of total use of chemical fertilizer was based on the empirical relationship between crop production and chemical fertilizer use during 1980–2018. The national predictions of major crops were calibrated with the CAMES estimates (Committee for Market Warning, 2021). Detailed additional information concerning the assumptions taken are provided in the SI.

2.3.2. Technical potential scenario

The TP scenario evaluates the physical mitigation potential of the best currently available technologies or practices, showing a conventional technology development path. A list of 48 production-side

Table 1
Basic assumptions in the BAU scenario.

	Unit	2018	2030	2040	2050	2060	Note
Population ^a	billion	1.39	1.46	1.45	1.40	1.33	Peaking at 1.46 in 2030
Urban population ^b	billion	8.3	1.04	1.11	1.12	1.11	The urbanization rate will be 80% in 2050
GDP ^c	trillion dollars, current price	13.9	25.1	35.4	45.8	54.0	–
per capital production ^d	beef	kg per capita	5.4	6.1	6.8	7.4	7.9
	pork	kg per capita	38.3	43.3	44.8	47.3	49.9
	mutton	kg per capita	3.5	4.2	4.7	5.0	5.3
	poultry meat	kg per capita	14.2	18.1	20.8	22.9	24.3
	milk	kg per capita	28.6	34.3	39.6	44.7	49.4
	egg	kg per capita	19.7	28.6	32.1	35.4	38.3

Data Sources.

^a UN Department of Economic and Social Affairs (2021a); National Bureau of Statistics NBS, 2021.

^b UN Department of Economic and Social Affairs(2021b).

^c Organisation for Economic Cooperation and Development OECD, 2021a; International Monetary Fund IMF, 2021; World Bank (2021)..

^d Based on analysis of multiple model results in this study.

technical options available to diminish emissions from the agricultural sector was developed, based on previous studies of technical options relevant to the agricultural sector in China and on a global level (Ahmed et al., 2020; Hristov et al., 2013; Uprety et al., 2012; Wang et al., 2014a). After consulting national agricultural experts on recent technology trends and conducting additional analysis of public literature, this study adopted a process to eliminate misclassification, limited projected impact, risk of overlap, or reduced long-term application (Ahmed et al., 2020). The resulting shortlist identified 11 technical options for the crop farming sector and 6 for the livestock feeding sector (Tables 2 and 3). The reduction efficiencies of multiple non-CO₂ GHGs were considered for each technical option, as most options displayed strong interactions with the sources of GHG emissions (Gerber et al., 2013). Despite their great relevance, the technologies or practices that reduced emission intensity only by increasing productivity and structural change were not included in the technology inventory. Consumption-based options were also not included because UNFCCC emission reduction targets are territory- and producer-based, and it is unlikely that this approach will be changed in the short term (Fellmann et al., 2018). This study also failed to predict breakthrough technologies in the long term or quantify the nonlinear spillover effects of agricultural mitigation technologies and practices.

The emission reduction potential (EP) (%) of each technical mitigation option *l* in year *y* and region *r* is yielded by its technical applicability (TA), implementation potential (IP), and reduction efficiency (RE) (Harmsen et al., 2019), as expressed in Eq. (2):

$$EP_{r,y,l} = TA_{r,y,l} \times RE_{r,y,l} \times \Delta IP_{r,y,l} \times OC_{r,y,l} \quad (2)$$

where TA is part of the baseline suitability covered by each measure (%), TA is often 100%, but smaller if a measure is not always suitable or only targets a subprocess; RE is the relative reduction of targeted emissions in comparison with a baseline case (%) averaged over multiple studies; IP increases over time owing to technology diffusion and implementation (%); and OC is the correction coefficient for overlap (%).

The reduction potential (RP) (MtCO₂-eq) in year *y* and region *r* is the combined effects of all mitigation options (USEPA, 2019a), as shown in Eq. (3):

$$RP_{r,y} = \sum_l EP_{r,y,l} \times BE_{r,y,l} \quad (3)$$

where BE is the targeted baseline emission (MtCO₂-eq).

2.3.3. Maximum technical potential scenario

The MTP scenario evaluates the upper limit of physical mitigation for China's agricultural sector without considering any technical, economic, or social implementation barriers across regions. The basic calculation process for the MTP scenario is the same as that of the TP scenario. However, the MTP scenario assumes complete application (TA = 100%) of all possible mitigation technologies by 2060. The values of TA, IP, and TP of each technology for the TP and MTP scenarios are listed in Tables S9 and S10 in the SI.

2.4. Uncertainty analysis and comparison with other studies

The AGHG-INV parameterization was verified by comparing historical estimates produced by the model to existing literature and official Chinese inventories over the period 1990–2018. Fig. 2 presents the results of the verification of total non-CO₂ GHG emissions against other essential studies, including estimates from the Electronic Data Gathering, Analysis, and Retrieval (EDGAR) system (Solazzo et al., 2021), Food and Agriculture Organization (FAO) of the United Nations (Tubiello et al., 2013), United States Environmental Protection Agency (USEPA) (USEPA, 2019a), Regional Emission inventory in ASia (REAS) version 2.1 (Kurokawa et al., 2013), and Chinese official national GHG inventories (1994, 2000, 2005, 2010, and 2014).

Table 2
Details of mitigation measures in the crop farming sector.

Technical mitigation options	Descriptions	Targeted non-CO ₂ GHG	Technical applicability
C1 Optimal fertilizer application	Reduce the overuse of synthetic nitrogen fertilizer by optimizing the amount	N ₂ O	All crops, mainly vegetable and fruit
C2 Formula fertilization by soil testing	It is a technology to determine the amount, period, and composition of nutrients (nitrogen, phosphorus, and potassium) and other trace elements based on soil testing and fertilizer field experiments. Since 2005, China has paid unprecedented attention to this technology.	N ₂ O, CH ₄ for rice	All crops
C3 Fertilizer nitrogen placement	Placement of nitrogen fertilizer into the soil near the zone of active root uptake will reduce nitrogen loss and increase plant nitrogen use resulting in a reduction in N ₂ O emissions.	N ₂ O	All crops
C4 N ₂ O inhibitor	Applying nitrification inhibitors (NI) or urease inhibitors (UI) to slow the microbial processes leading to N ₂ O formation	N ₂ O, CH ₄ for rice	All crops
C5 Slow release fertilizer	Slow-release of urea and NH ₄ based fertilizers can be achieved by using various coatings, chemical modifications, and changing the size of fertilizer granules.	N ₂ O, CH ₄ for rice	All crops
C6 Efficient irrigation practices for upland crops	Applying more efficient irrigation technologies, such as springer or drip irrigation to control soil microbial activity and substrate supply for N ₂ O formation	N ₂ O	Upland crops
C7 Biochar	Biochar is a highly stable carbon compound that is carbonized by crop residues. It is carbon-rich fine-grained, has a highly porous structure and increased surface area that makes it an ideal soil amendment for carbon sequestration and GHG mitigation.	N ₂ O	All crops
C8 Conservative tillage	A series of agricultural practices aim to reduce tillage and soil disturbance to a minimum extent, with at least 30% of residues incorporated into the soil to increase the soil carbon content.	N ₂ O	Upland crops
C9 Water management for rice	A series of water management practices, such as mid-season water drainage and alternate wetting and drying (AWD) to save water and control CH ₄ emission from rice paddy The biotechnology approach for CH ₄	CH ₄ CH ₄	Rice Rice

(continued on next page)

Table 2 (continued)

Technical mitigation options	Descriptions	Targeted non-CO ₂ GHG	Technical applicability
C10 Low CH ₄ emitting rice varieties	mitigation technology involves the identification of rice cultivars that emits less CH ₄		
C11 CH ₄ inhibitor	Additives that can control the microbial process of CH ₄ formation	CH ₄	Rice

Source: Wang et al., 2014a; Uprety et al. (2012)..

It can be seen that the AGHG-INV estimates exhibit similar temporal trends and are entirely in line with the other reports. The discrepancy amongst these results is attributed primarily to the selection of both activity data and EFs. Activity data in EDGAR, FAO, USEPA, and REAS, which were derived from the FAO, showed substantial differences from the Chinese statistical data (Solazzo et al., 2021; Yu et al., 2018; Zhuang et al., 2019). Moreover, unlike EDGAR, FAO, USEPA, and REAS, which usually use IPCC defaults (Kurokawa et al., 2013; Solazzo et al., 2021; Tubiello et al., 2013; USEPA, 2019a), the AGHG-INV model adopted the median values of the data reported in existing studies of China for the EFs and applied regional parameters to calculate province-specific EFs. In general, the AGHG-INV model is consistent with national inventories. The differences range between -27% and 15%, with a probability of more than 60% less than 3% of the difference. The most notable discrepancy relates to agricultural soils where the national inventory applies the Improving Anthropogenic Practices of managing reactive Nitrogen model to evaluate the N₂O emissions of farmland. The uncertainty associated with the AGHG-INV model was derived from the activity data and EFs (Zheng et al., 2008).

3. Results and discussion

3.1. National emission trajectories to 2060 of non-CO₂ GHGs from agriculture

Based on the AGHG-INV model, agriculture sector emissions can be projected until 2060. Fig. 3 shows the evolution of CH₄ and N₂O emissions in China from agricultural sources for the three different scenarios considered. Between 1980 and 2018, national agricultural non-CO₂ emission levels rose by approximately 34%, from 646 to 856 MtCO₂-eq yr⁻¹. Over this same period, emissions of CH₄ and N₂O increased by 17% and 86%, respectively.

The BAU scenario projects non-CO₂ emissions from China's agricultural sector to increase by approximately 33% (range: 24%–41%) during 2018–2060, thereby reaching 1153 MtCO₂-eq yr⁻¹ (range: 992–1315 MtCO₂-eq yr⁻¹). During the same period, emissions of CH₄ and N₂O are expected to increase by 42% and 15%, respectively. The projected rate of growth of emissions is moderately lower than that of the FAO. It is projected that by 2050 agricultural non-CO₂ emissions in China will increase by 33%, whereas the FAO projects the increase to be 37% (Tubiello et al., 2013).

In comparison, the forecast by the USEPA is very positive because it projects that non-CO₂ emissions from Chinese agriculture will increase by less than 2% by 2050. CH₄ emissions have stabilized since 2000, mainly due to government policies, such as the stabilization of agricultural production (Xu et al., 2017) and stricter environmental management (Qian et al., 2018). However, as dietary requirements continue to shift, CH₄ emissions from enteric fermentation of dairy cows, cattle, and buffalo are expected to increase from 2020 onward, accounting for 77% and 56% of the increments from 2018 to 2030 and from 2030 to 2060, respectively, under the BAU scenario. In China, the consumption of ruminant meat and dairy products increased exponentially from the early 1990s and from the early 2000s, respectively (Du et al., 2018; Yu

Table 3

Details of mitigation measures in the livestock feeding sector.

Technical mitigation options	Descriptions	Targeted non-CO ₂ GHG	Technical applicability
L1 Feed supplements	To optimize the synthetic or metabolic pathway of microorganisms related to CH ₄ synthesis by employing modern molecular biotechnology to obtain genetically modified microorganisms.	CH ₄	All ruminant's system
L2 Feed quality improvements	To optimize the concentrate to forage ratio in the diet by controlling the crude fiber content of the diet or the fermentation process to reduce CH ₄ emission while ensuring the average production performance of animals.	CH ₄	All ruminant's system
L3 Low CH ₄ emitting breeds	Breeding techniques like artificial insemination of domestic livestock with high-quality semen from breeding stock will decrease CH ₄ production and improve feed intake and production efficiency.	CH ₄	All ruminant's system
L4 Best timing of manure storage	Storage treatments that provide aeration, such as mechanical or intermittent aeration, have been shown to reduce CH ₄ emissions. Other options include decreasing manure temperature, removing the manure from the building, and storing waste outside in cold climates.	CH ₄	All animal's system
L5 Composting	Composting is an exothermic and aerobic process of microbial decomposition of organic matter. The addition of mature compost with nitrite-oxidizing bacteria to actively composted manure was shown to reduce N ₂ O emissions, but the primary benefit of composting is that it reduces CH ₄ emissions.	N ₂ O, CH ₄	All animal's system
L6 Anaerobic digester	Anaerobic digestion is the process of degradation of organic materials by archaea in the absence of oxygen, producing CH ₄ , CO ₂ , and other gases as by-products and is a promising practice for mitigating GHG emissions from collected manure. In general, reducing organic matter content is expected to reduce N ₂ O emissions from manure-amended soils.	N ₂ O, CH ₄	All animal's system

Source: Wang et al., 2014a; Uprety et al. (2012); Gerber et al. (2013); Hristov et al. (2013)..

et al., 2016). During 2000–2017, the per capita consumption of meat, milk, and eggs increased by 75%, 150%, and 38%, respectively (Liu et al., 2021b). The total demand for ruminant products in China is predicted to double by 2050, which will be the fundamental driving force for increasing CH₄ emissions (Du et al., 2018). For this same reason, manure management emissions are also projected to increase, accounting for 12% of the total increment from 2018 to 2060. There is great uncertainty regarding future changes in the dietary habits of

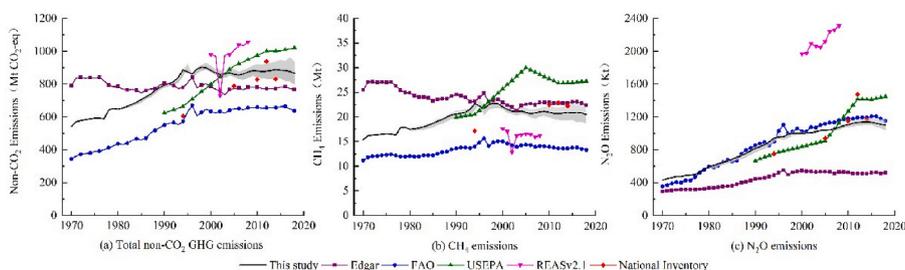


Fig. 2. Comparison of historical results produced by the AGHG-INV model with data from other sources.

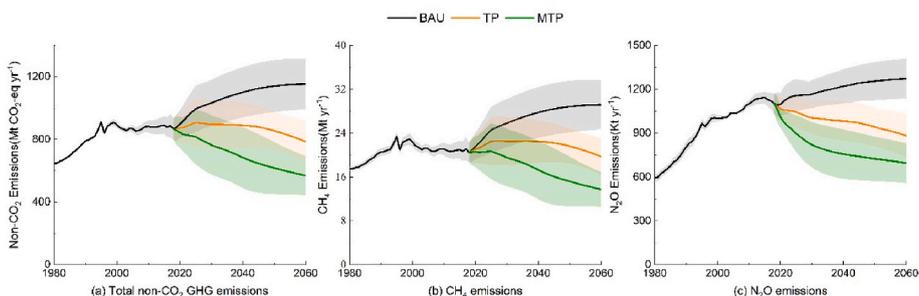


Fig. 3. Projected emission trajectory under the three scenarios: (a) total non-CO₂ GHG emissions, (b) CH₄ emissions, and (c) N₂O emissions.

Chinese people, and the projection of animal-based products varies by more than 40%. With the implementation of policies and practices to control chemical fertilizer inputs, N₂O emissions from agricultural soils will only increase by 28 ktCO₂-eq over the study period, contributing less than 8% of the total increment.

Adopting mitigation technologies will enable China’s agricultural non-CO₂ GHG emissions to peak much earlier and reduce in magnitude by 2060. Under the TP scenario, agricultural emissions are projected to peak at 907 MtCO₂-eq yr⁻¹ (range: 756–1057 MtCO₂-eq yr⁻¹) in 2025, and future non-CO₂ emissions reducing by 32% (range: 30%–35%) by 2060 (Fig. 3). In 2030, the technical mitigation potential in Chinese agriculture will be 136 MtCO₂-eq yr⁻¹ (range: 133–140 MtCO₂-eq yr⁻¹). With technology diffusion, the technical mitigation potential in Chinese agriculture will amount to 284 MtCO₂-eq yr⁻¹ (range: 243–326 MtCO₂-eq yr⁻¹) and 367 MtCO₂-eq yr⁻¹ (range: 339–396 MtCO₂-eq yr⁻¹) in 2050 and 2060, respectively. This result, which is in reasonable agreement with global and multimodel results, indicates that 30%–94% of the total reduction in emissions (330–750 MtCO₂-eq yr⁻¹) by 2050 would be realized through adoption of technical options (Frank et al., 2019; Lin

et al., 2019). The most considerable mitigation potential is related to rice cultivation and livestock feeding (including enteric fermentation and manure management), accounting for 34% and 34%, respectively, of the total mitigation potentials in 2060 (Fig. 4). Agricultural soils also present notable mitigation of approximately 92 MtCO₂-eq yr⁻¹, contributing 25% to the full mitigation potential.

The MTP scenario will cut emissions further by 28% and 51% in comparison with the TP scenario and the BAU scenario, respectively, which represents 268 MtCO₂-eq yr⁻¹ (range: 228–307 MtCO₂-eq yr⁻¹), 522 MtCO₂-eq yr⁻¹ (range: 521–531 MtCO₂-eq yr⁻¹), and 585 MtCO₂-eq yr⁻¹ (range: 549–621 MtCO₂-eq yr⁻¹) in 2030, 2050, and 2060, respectively. The largest reduction potential in the agricultural sector under the MTP scenario relates to livestock management, including improved manure management and reduced enteric fermentation through better feed composition and feed supplements. It contributes to 46% of the total mitigation potential under the MTP scenario, whereas rice cultivation will account for 29% of the total mitigation potential (Fig. 4).

Considering that there are uncertainties concerning which GWP to be

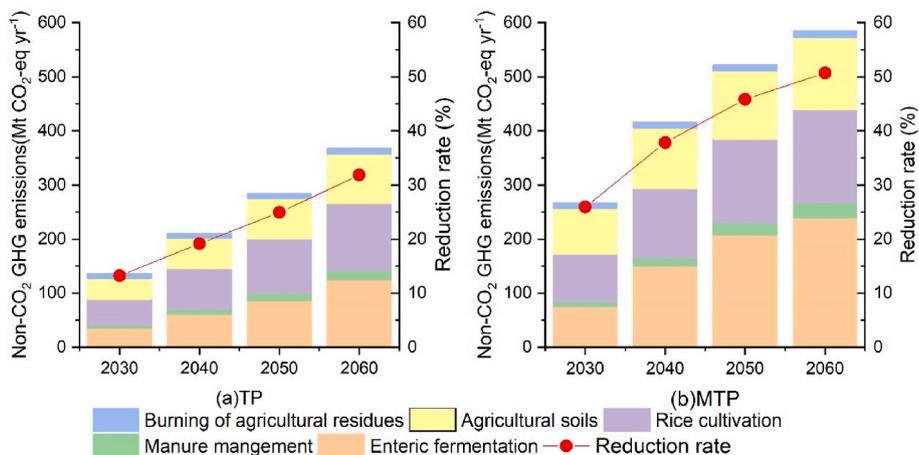


Fig. 4. Projected mitigation potentials of different subsectors under (a) the TP scenario and (b) the MTP scenario in comparison with the BAU scenario.

applied in the future, a sensitivity assessment was performed comparing the results for GWP₁₀₀ and GWP₂₀ values in IPCC AR5 and AR6. As shown in Fig. 5, total non-CO₂ GHG emissions from the agricultural sector are very sensitive to GWP values. Adopting GWP with shorter lifetimes, i.e., GWP₂₀, will amplify the contribution of non-CO₂ GHG emissions from agricultural sources and the possible GHG reduction achieved by applying mitigation measures because the importance of CH₄ will increase. Additionally, converting to GWP₁₀₀ values in AR6 will reduce the total non-CO₂ GHG emissions in all scenarios in the agricultural sector by 32%, while increasing N₂O 's contribution. By contrast, the conversion of GWP₂₀ values to those in AR6 only caused a decline of about 5%. However, the effect of this conversion differs between years and regions. For the same period and region, there is little difference between scenarios.

3.2. Regional and provincial emission trajectories to 2060 of non-CO₂ GHGs from agriculture

The absolute and relative importance of agricultural emissions within regions and provinces in China have a diversified structure. Under the BAU scenario, non-CO₂ GHG emissions from agricultural sources in all six regions of China (Northwest, Southwest, South Central, Eastern, Northeast, and Northern) will gradually increase, as shown in Fig. 6. Their contribution to the national totals will remain approximately constant. South Central China and Southwest China contributed the greatest share of agricultural non-CO₂ GHG emissions in 2018, accounting for 26% and 23% of the national total, respectively. These two regions are also important agricultural production areas, particularly the livestock feeding sector. They are followed by Eastern China, which contributed 19% to the national total in 2018. The three regions also have immense mitigation potentials in 2060.

Under the TP scenario, South Central China, Southwest China, and Eastern China will have mitigation potentials in 2060 of 98, 89, and 74 MtCO₂-eq yr⁻¹, respectively, reflecting a rate of reduction of 35%, 34%, and 25%, respectively. Their contribution to the total mitigation potential in the Chinese agricultural sector will reach 27%, 25%, and 20%, respectively. Under the MTP scenario, these three regions still have mitigation potentials of 151, 143, and 113 MtCO₂-eq yr⁻¹, respectively, with reduction rates of 54%, 54%, and 57% that account for 25%, 24%, and 19% of the total mitigation potentials, respectively.

Fig. 7 illustrates the temporal trajectories of non-CO₂ GHG emissions from 1980 to 2060 under the three scenarios. Under the BAU scenario, Gansu, Xinjiang, Ningxia, and Inner Mongolia will record rapid rates of growth of non-CO₂ GHG emissions from agricultural sources. From 2018

to 2060, the emissions will increase by more than 40%–50% under the BAU scenario for the four provinces, attributable mainly to the rapid growth of ruminants and emissions from enteric fermentation. Under the TP scenario, emissions in the four provinces will reduce by approximately 27%–28% in 2060, but in comparison with the levels of 2018, emissions will increase by 20% in 2060 and peak at around 2046–2048. Profound reduction under the MTP scenario will reduce emissions from the four provinces by 20%, and emissions will peak at 2032–2033 with a decrease of peak emissions by approximately 20% in comparison with the levels under the TP scenario. Hebei, Shandong, Shanxi, Heilongjiang, Liaoning, and Jilin will also see rapid growth of non-CO₂ GHGs at a rate of approximately 40%. However, the drivers of such increases in these provinces differ from those of the first group; rice cultivation and agricultural soils will be the primary sources for the emission increments.

Under the TP and MTP scenarios, emissions in the six provinces will reduce by 25%–32% and 40%–50%, respectively. Although the six provinces will see a moderate increase in emissions, the peak will be around 2045–2047 under the TP scenario. However, under the MTP scenario, the year of peak emissions in the six provinces will vary. Some provinces, such as Liaoning, will have a decreasing trend from 2018 to 2060, but Heilongjiang will peak in 2032, Jilin in 2033, Shanxi in 2034, and Hebei and Shandong in 2035. Sichuan and Yunnan, the top emitters of non-CO₂ GHGs both in 2018 and in 2060, account for approximately 18% of the total emissions and they will also see increases in emissions of 23.6% and 27.3%, respectively, in comparison with those in 2018. Under the TP and MTP scenarios, Sichuan and Yunnan will have trends of declining emissions, i.e., the emissions in the two provinces will decrease by 36%–43% and 53%–60%, respectively, in comparison with the levels in the BAU scenario. By contrast, regions in eastern or central areas, such as Zhejiang, Fujian, Jiangsu, Anhui, Guangdong, and Chongqing, will see very moderate rates of increase of less than 10% under the BAU scenario and very significant trends of decrease in emissions under both technical scenarios.

3.3. Technical mitigation potentials of listed measures

Stand-alone abatement potentials of the 17 listed mitigation measures are presented in Fig. 8. For the crop farming sector, the most effective measures with the highest mitigation potentials under the TP scenario will include water management for paddy fields (C9), efficient irrigation practices for upland crops (C6), and slow-release fertilizers (C5), which will have mitigation potentials of 45, 34, and 33 MtCO₂-eq yr⁻¹, respectively, in 2060. Suppose mitigation could be promoted with

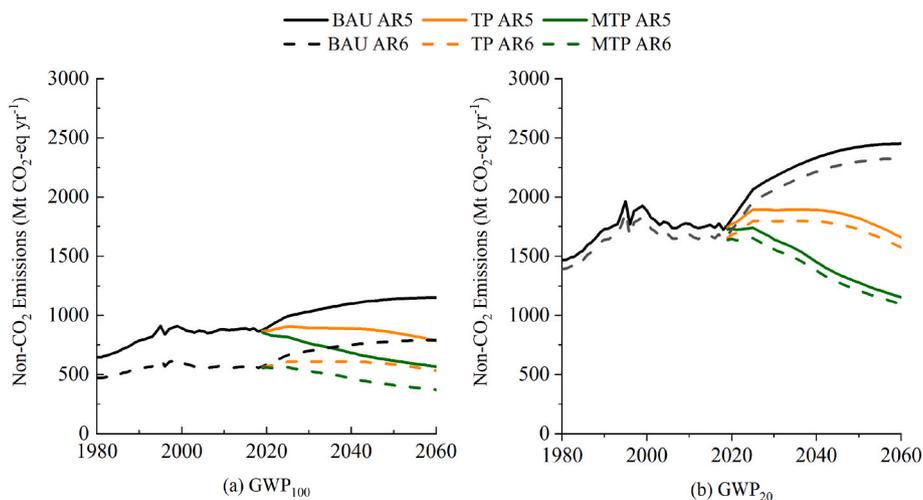


Fig. 5. Total non-CO₂ GHG emissions by the scenarios from 1980 to 2050: (a) total non-CO₂ GHG emissions using GWP₁₀₀ values in IPCC AR5 and AR6, and (b) total non-CO₂ GHG emissions using GWP₂₀ values in IPCC AR5 and AR6.

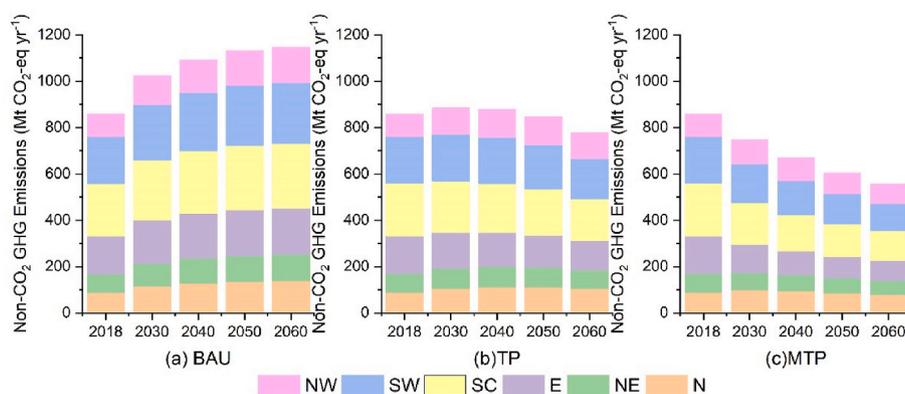


Fig. 6. Regional emission trajectories in 2030, 2040, 2050, and 2060 for (a) the BAU scenario, (b) the TP scenario, and (c) the MTP scenario (NW: Northwest China; SW: Southwest China; SC: South Central China; E: Eastern China; NE: Northeast China; and N: Northern China).

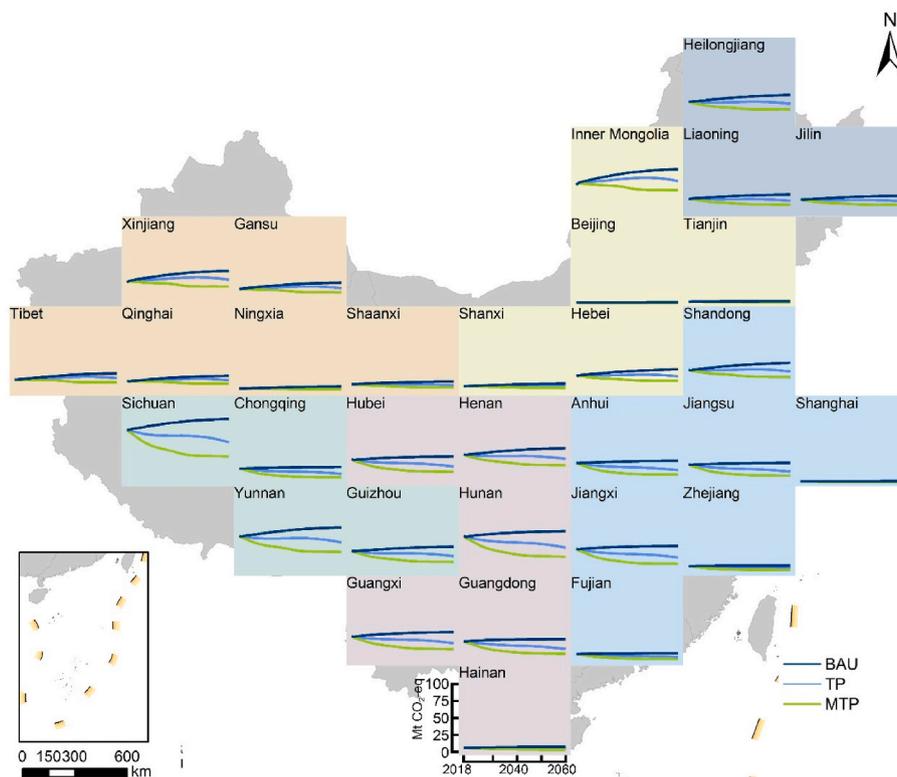


Fig. 7. Emission trajectories of agricultural non-CO₂ GHG emissions at the provincial level in China.

the most ambitious objectives and minimal cost considerations. In that case, an N₂O formation inhibitor (C4) and slow-release fertilizers (C5) would be the most promising mitigation options in 2060. In 2060, their mitigation potentials could amount to 64 and 53 MtCO₂-eq yr⁻¹, respectively, under the MTP scenario. For the livestock feeding sector, however, the most promising two options are feed supplements (L1) and feed quality improvements (L2), which would have mitigation potentials of 50–74 and 100–134 MtCO₂-eq yr⁻¹ in 2060 under the two technical scenarios.

This study analyzed only a limited set of specific technological GHG mitigation options. Under the TP and MTP scenarios, AGHG-INV model assumed different levels of adoption of new technologies by farmers. The study is limited by the fact that it did not consider technologies that could enhance agricultural productivity or structural changes that have proven to have substantial mitigation potentials in Europe and at the global level (Fellmann et al., 2018; Frank et al., 2018). Future research

can examine additional options based on more detailed inventories and broader assumptions of applicability, such as productivity advances, structural changes, and consumption trends. Nevertheless, our results strongly indicate that an effective mitigation strategy should also consider options that tackle the reduction of emissions from the consumption side, especially regarding meat products. The GHG emission trajectories are affected substantially by the trends of future animal-sourced food products.

3.4. Limitations of the estimates

It is imperative to interpret the results within the boundaries of the information available and the analytical capabilities available, especially for long-term forecasts. The sensitivity analysis shows that basic assumptions regarding the demographic, social, and economic developments of China have substantial impact on the magnitude of

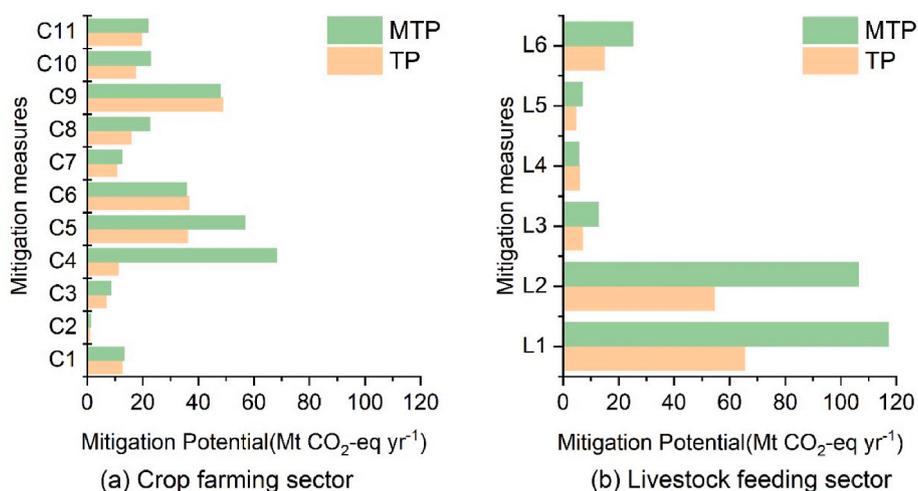


Fig. 8. Mitigation potentials in 2060 of different mitigation measures: (a) cropping farming sector and (b) livestock feeding sector.

emission reductions under the BAU scenario, but less on the relative proportions of mitigation potentials. Additionally, this assessment was mainly built on IPCC Tier 2 methodologies, which generally provide estimates with a higher level of uncertainty than that of a Tier 3 method for historic trends (IPCC, 2006). However, Tier 2 methodology comprised uncertainties for historical trends and future projections, as Tier 3 methodology depends on high-resolution data, such as climate, soil, and land use. However, obtaining reliable long-term datasets with the high spatial resolution isn't easy. For example, the most recent high-resolution soil data available for China is from the second National Soil Census between 1978 and 1984 (Shi and Song, 2016). The third National Soil Census will start in 2022. Using the data for long-term assessment will introduce new uncertainties.

Furthermore, it is technically challenging to project the spatial and temporal change of activity data, emission factors, and those critical climatic and environmental parameters in the future. Tier 3 methodology is currently only applied to depict GHG emissions from a specific sub-sector for a particular historical year instead of long-term scenario analysis, such as Cui et al. (2021) and Wang et al. (2020b). It also highlights that further developments and research are needed to improve the assessment of current emissions and projections.

Another limitation of this assessment is that the EFs do not evolve over time owing to the limited information available regarding the temporal evolution of country-specific EFs for China. Further assessments of the historical temporal dynamics of EFs for China and studies of climate-related dependencies for major EFs will undoubtedly elucidate these dynamics.

Nevertheless, the net differences projected in the sensitivity analysis are meaningful when compared across key sources of uncertainty. The approach to testing the sensitivity of future emissions in our analysis using upper (or optimistic) and lower (pessimistic) levels of estimated mitigation is an example of how such issues could be assessed. As more and more datasets concerning local emission factors and activity data sources become available, our ability to estimate and project GHG developments at the local scale with greater precision will ultimately improve.

3.5. Policy implications for carbon neutrality

This study revealed the importance of technology in achieving China's carbon neutrality objective. However, the potential of such technology lies not only in the production-side mitigation measures, which were evaluated in this study, but also in the improvement of agricultural productivity (Du et al., 2018), structural measures (Frank et al., 2018), and consumption-side measures (Frank et al., 2019). Some

studies illustrated that the application of current technologies or practices to boost productivity could also markedly reduce agricultural emissions, specifically from the production of maize (Liu et al., 2021b) and from the livestock sector (Chang et al., 2021). Thorough assessment of all technical options would support prioritization of the development and diffusion of the technology most suitable for reducing agricultural emissions.

Furthermore, although technological improvement has the potential to mitigate emissions from the agricultural sector, its implementation faces a series of socio-economic obstacles (Ahmed et al., 2020), particularly in relation to the less-consolidated agriculture sector. Farm size also plays a critical role in the adoption of new technologies. With 200–300 million households, each of which farms a few hectares of land, the Chinese agricultural system relies heavily on high-to-excessive inputs (Cui et al., 2018). A study in Jiangsu Province revealed that almost 90% of the surveyed farmers worked less than 10 Mu (0.67 ha) of arable land. This fragmentation contributes to the inefficient use of agricultural inputs such as chemical fertilizers (Hu et al., 2019a). Research has shown that farmers with large farms are more likely to adopt new technology because they can afford to devote part of their land to trials, and because some bulky technologies require economies of scale to ensure profitability (Hu et al., 2019b; Yue et al., 2019; Wang et al., 2020a). Moreover, the risk of failure or accepting lower yields in the short term, even for the sake of long-term gains, is untenable for many Chinese farmers who are usually risk-averse. Results indicate that if the probability and elasticity of fertilizer use are high, risk-averse farmers apply more fertilizer than risk-taking farmers (Qiao and Huang, 2021). Similar results can be found in other cases, where risk-averse farmers are more reluctant to adopt new technology (He et al., 2019; Mao et al., 2019). This will require effective policy instruments to create suitable incentives.

This study also revealed that accounting for the key interferences is essential to find the actual trajectories of agricultural GHG emissions as well as the true cost of mitigation options, such as the interdependencies of crops and livestock, interactions between multiple gas emissions, and impacts of GHG mitigation on other environmental properties (McCarl and Schneider, 2001). Owing to the heterogeneity of agriculture, the composition of the portfolio of strategies or measures varies regionally. There will be no one-size-fits-all policy or option for mitigation of GHG emissions in the agricultural sector, which will negatively impact implementation of mitigation policies on the ground and increase implementation costs. In this context, designing a multistrategy program that provides farmers some flexibility to choose the option most suited to the regional or local characteristics might facilitate policy acceptance.

These challenges represent considerable obstacles that might

account for the lack of focus of policymakers on agricultural emissions. Currently, merely 38% of global agricultural emissions are covered by nationally determined commitments under the Paris Agreement (Ahmed et al., 2020). China submitted its first nationally determined contribution in February 2016, which proposes the goal of reducing CO₂ emissions per unit GDP by 60%–65% below 2005 levels by 2030. It also explicitly outlines plans to implement programs and measures in different sectors to support achievement of mitigation targets. Although no measurable target was addressed for agriculture, several measures were highlighted that included promoting low-carbon development, encouraging efforts to achieve zero growth of fertilizer and pesticide use by 2020, controlling CH₄ emissions from paddy fields and N₂O emissions from farmland, and promoting recycling within the agricultural system. This is not unusual because agriculture is mentioned by 121 countries as the sector in which emission reductions are intended, but where only a few countries have set quantitative targets (Fellmann et al., 2018). However, the objective of carbon neutrality places the agricultural sector back into focus. Agriculture should not be let off the hook regarding the mitigation of GHG emissions globally.

4. Conclusions

This study projected the future trend of non-CO₂ GHG emissions from China's agricultural sector and examined how best to structure a province-based emission reduction pathway to support China's objective of being carbon neutral before 2060. The analysis indicates that due to the larger and more affluent population and rapid changes in dietary requirements, China's agricultural emissions will continue to rise by 33% by 2060 in the absence of targeted mitigation efforts in the agriculture sector. In order to reduce China's agriculture emissions, technology can play a crucial role. With the best technologies or practices available today, agricultural emissions in China will peak around 2025 and will decrease by 32% by 2060. Additionally, if regional technical, economic, and social barriers to implementation are overcome, emissions can be further reduced by 28%, and the most notable mitigation potential is related to livestock management. The most effective mitigation measures include feed supplements, feed quality improvements, slow-release fertilizers, and improved water management for paddy fields and uplands. However, it should be noted that the agricultural sector, not only in China but also in other places, usually has a complex set of objectives to consider alongside climate goals, e.g., nutritional needs, food security, and the livelihoods of farmers. As a result, realizing the estimated mitigation potential in the agricultural sector may be more challenging than in other sectors.

Generally, there is wide heterogeneity in mitigation potential within the agricultural sector, which differs across regions. All six regions of China will gradually increase non-CO₂ GHG emissions from agricultural sources, and their contribution to the national total will remain approximately constant. South Central China and Southwest China continue to have the greatest share of agricultural non-CO₂ GHG emissions, accounting for 23%–26% and 22%–23% of the national total, respectively. The two regions will also have the greatest share of mitigation potentials under the two technical scenarios. There are diversified structures of emissions for different provinces. For example, Gansu, Xinjiang, Ningxia, and Inner Mongolia will record the fastest growth owing to the dramatic increase in the number of ruminants. Regions in eastern or central areas such as Zhejiang, Fujian, Jiangsu, Anhui, Guangdong, and Chongqing will see very moderate rates of increase of less than 10%, even under the BAU scenario.

The study also identified numerous other research priorities relevant to the challenge of achieving carbon neutrality in Chinese. First, since the majority of technology information can only be derived from meta-analyses of published literature and expert consultation, developing a more detailed inventory of "real" mitigation measures in production will be essential based on a survey of typical regions. Second, the behavior of farmers plays a critical role in the adoption of mitigation measures.

Therefore, accurate estimates of mitigation potentials rely on understanding the determinants of farmer behavior, as well as identifying the policy instruments necessary to change their behavior. Third, further research could focus on the interaction of mitigation, productivity, and other socio-economic drivers in China's agricultural sector, particularly on the risk related to pollution swapping and other possible unintended impacts of mitigation.

CRedit authorship contribution statement

Minpeng Chen: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Yanrong Cui:** Data curation, Formal analysis. **Shan Jiang:** Data curation, Investigation. **Nicklas Forsell:** Conceptualization, Writing – original draft, 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2022.133186>.

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