Modelling Greenhouse Gas Fluxes from China's Agriculture, Forestry and Land Use Sector:

Gaps and recommendations

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Contents

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Executive summary

This assessment evaluates existing greenhouse gas (GHG) projections for the Chinese agriculture, forestry and land use (AFOLU) sector and the models being used to create them. A total of eight models (GLOBIOM-China, MAgPIE-China, GCAM5.3, FABLE Calculator-China, ORCHIDEE, PECE-LIU, AGHG-INV and SRNM) are compared and analysed for their coverage of sectors, carbon pools, land use categories, and projections.

In terms of the land use, land use change, and forestry (LULUCF) sector, the models variously cover the most relevant land use categories: forest land, grassland, and cropland. The Intergovernmental Panel on Climate Change (IPCC) tier methods used and the coverage of specific carbon pools differ widely between the models. In the agricultural sector, the eight models have some similarities in their structure and scope, with Tier 2 dominating for the calculation of GHG fluxes.

There are significant uncertainties in existing model estimates regarding historical and projected future LULUCF emissions and removals for China. The difference in historical net emission estimates between the models is striking, at 1,119 million tons of carbon dioxide equivalent ($MtCO_2eq$), which corresponds to the estimated size of China's national GHG sink in 2014 (1,150 $MtCO_2eq$). In terms of future developments of the LULUCF sector, the models cannot provide a unified picture as to whether China's current national GHG sink will increase or decrease.

For the agricultural sector, most models project a business-as-usual development in which the non-CO_2 emissions (mainly CH_4 and N_2O) from China's agricultural sector increase at a much more moderate rate after 2030, and peak between 2045 and 2060. The peak emission projections range from 800 to 1,400 $MtCO_2eq$. The future mitigation potential estimates for agriculture range from 200 to 800 $MtCO_2eq$. The ranges reflect differences in base years, model structure, scenario assumptions, and parameter selection.

As a whole, the models differ considerably in their representations of the Chinese AFOLU sector. As a result, caution is needed when comparing projections and when using them to formulate policy targets. The assessment thus highlights the need for prioritized actions and further development of the Chinese AFOLU sectorial models so that they can assist in setting targets and developing reliable and clear pathways for the AFOLU sector in line with limiting global warming to 1.5°C or well below 2°C. Priority actions include more collaboration in model development, better data sharing and access, and promoting multi-model comparison.

1. Introduction

The Paris Agreement sets a long-term target of keeping the increase in global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C. To achieve the temperature goals, countries will need to plan for a profound and rapid transformation of all sectors. Forestry and agriculture activities are integral to any mitigation strategy for greenhouse gas (GHG) emissions and removals. Land management and land use change activities in these sectors can act as a source of GHG emissions – including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – or as a sink. Carbon sinks are defined as carbon pools, other than the atmosphere, where CO_2 is removed from the atmosphere by sequestration.

Globally the agriculture, forestry, and other land use (AFOLU)[i] sector is responsible for the gross emissions of approximately 11.2 gigatons of carbon dioxide equivalent per year ($GtCO_2eq$ per year).[2,3,4] This is about 25% of all net anthropogenic GHG emissions, with nearly half of the amount coming from agriculture and half from land use change.[5,6,7] At the same time, the economic mitigation potential within the land use sector is substantial: removals from the land use, land use change, and forestry (LULUCF)[ii] sector are estimated at between 1.9~2.1 and 3.1~3.3 $GtCO_2eq$ per year at a carbon price of USD 20 and USD 100 per t CO_2eq by 2030, respectively.[8] Furthermore, around 1 $GtCO_2eq$ per year of emissions from the agriculture sector could be mitigated by 2030 at a carbon price of USD 25 per tCO_2eq.

While there is significant mitigation potential within the land use sector, the demands on the sector are also increasing – for the provision of food, biomass, biodiversity, and tourism – creating challenges for land use planning. A recent systematic literature review and meta-analysis suggest that global food demand will increase by 35 to 56% between 2010 and 2050, driven by population increase and changing diets. On a global level, total GHG emissions from agriculture continue to grow at approximately 1% per year, and agriculture is expected to remain one of the most significant contributors to world emissions in 2030.[9,10,11] Under a 1.5°C scenario, the global AFOLU sector could feasibly and sustainably contribute about 30%, or 15 $GtCO_2eq$ per year, of the global mitigation needed in 2050 (including bioenergy with carbon capture and storage, or BECCS). This will require a transformation of the AFOLU sector worldwide, both production and consumption aspects.[12]

On September 22nd 2020, at the general debate of the 75th session of the United Nations General Assembly, China announced that it was aiming for carbon neutrality before 2060, demonstrating its determination to pursue a new model of economic growth and development. The transformation will be profound and comprehensive, but benefits and impacts will be unevenly distributed across sectors and regions. With almost 18% of the world's population, food security is a top priority in China's national socio-economic development strategies and plans. With the population expected to peak at 1.45 billion in 2024, and diets shifting towards more animal-based protein, most business-as-usual (BAU) scenarios project non-CO_2 GHG emissions from the agriculture sector to increase, making it more challenging for the country to decarbonise.[13] From 1994 to 2014, non-CO_2 GHG emissions from China's agricultural sector increased by about 37%, while the LULUCF sector was a net carbon sink.[14] To achieve a 1.5°C-consistent pathway for China, GHG emissions from the agricultural sector alone will need to peak by 2030, and the LULUCF sector must continue its role of net carbon sink.[15] However, unlike other sectors (including energy, transportation, and industry), there is limited knowledge surrounding feasible and sustainable mitigation strategies, goals, and roadmaps for reducing non-CO_2 GHG emissions and

i. The agriculture, forestry and other land use (AFOLU) term encompasses agriculture as well as the land use, land use change and forestry (LULUCF) category.

ii. Following the 2006 IPCC guidelines, the LULCUF sector includes reporting of fluxes related to changes within and conversions between all land use types including: forest land, cropland (including the soil carbon pool), grassland, wetlands, settlements and other land. The sector also includes reporting of fluxes related to changes to the harvested wood products pool.

enhancing carbon sinks in the AFOLU sector in China. Building this knowledge will require a systematic, comprehensive, and in-depth analysis of long-term emission trajectories, their temporal and spatial characteristics, possible technology options, technical and economic mitigation potentials, and the economic impacts of mitigation technologies or practices in the AFOLU sector.

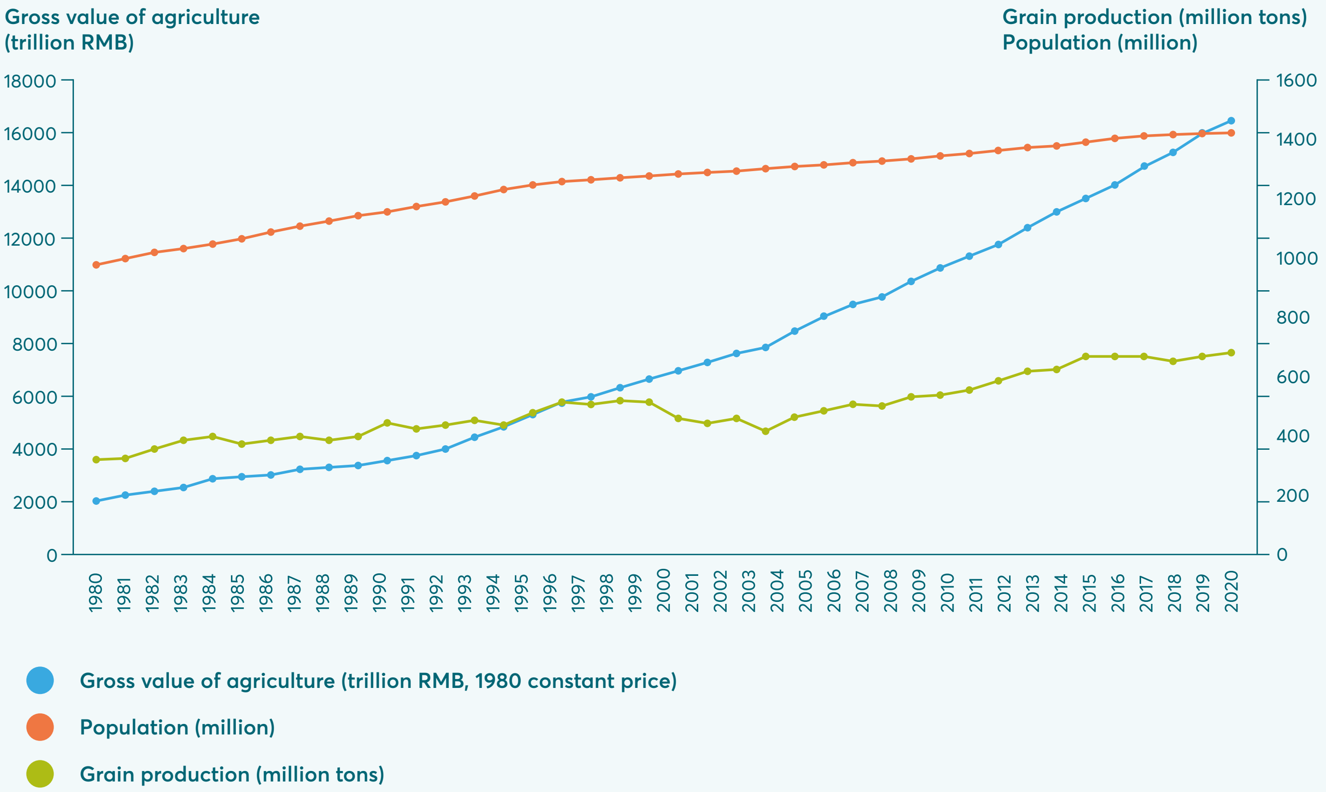
In this context, this study conducted a systematic analysis of existing economic and biophysical models that simulate future potential GHG emissions and removals, land cover change, and commodity production in the Chinese AFOLU sectors. The assessment analysed and identified similarities and critical differences between the models themselves and their existing projections of GHG emissions and removals for China. We explored the key features of the different modelling tools and assessed how the underlying differences in modelling characteristics influence the projections, including critical assumptions, regional and sectoral coverage, coverage of carbon pools and gases, and the inclusion of mitigation technologies and mitigation options. Based on this analysis, we evaluate the uncertainty ranges of future emissions and removals for the Chinese AFOLU sector. We conclude with some recommendations for closing the knowledge gaps to improve future model development.

2. China's agricultural development and GHG fluxes

China has a long farming history with a tradition of intensive cultivation, and a substantial rural population. Agriculture has long been the bedrock of China's political and economic stability, and the Chinese government has placed a high priority on its development. Since 1978, China has succeeded in producing one-fourth of the world's grain and feeding one-fifth of the world's population from less than 10% of the world's arable land,[16,17] which is a major achievement for food security in China and the world. Currently, China ranks first in the world for the production of cereals, cotton, fruit, vegetables, meat, poultry, eggs, and fishery products, and has built up agricultural exchange and co-operation relations with more than 140 countries worldwide.[18]

Figure 1 gives an historical overview of China's agricultural economy. The agriculture sector has grown steadily since 1990. Growth slowed after 1997, but took off again from 2003. Since 2008, agriculture has contributed to total factor productivity (TFP) growth as much as China's non-agricultural sectors.[19,20] From 2000 to 2020, domestic grain production and the total output value of agriculture increased by 45% and 139% respectively (in 1980 constant prices), with intensification and growth of high-value agricultural products (vegetables, fruit, meat, milk, etc.) playing a critical role.[21] Despite the challenges posed by COVID-19, plant pests, and natural disasters, China saw its 17th consecutive bumper year in 2020, with grain output up 0.9% year-on-year to nearly 670 billion kg in 2020. It marked the ninth consecutive year the country's total grain production exceeded 600 billion kg, a production of a good harvest. The annual policy blueprint, known as the "No.1 document", placed greater emphasis on food security than in 2021, calling for all provinces to improve grain yields during the 14th five-year period (2021-2025) as the pandemic hit top food-exporting nations and raised concerns about the stability of food supplies.

Figure 1: Historical trends in China's agricultural sector



Data Source: National Bureau of Statistics, 2022[22]

Along with the increase in agricultural productivity and income levels, the dietary structure of the population has changed dramatically, with a steady increase in the consumption of animal foods such as red meat, poultry meat, dairy and eggs, which poses a major health and environmental challenge for China.[23] In 2019, per capita staple food consumption (i.e. rice, maize, wheat, and other grains) was 145.8kg, down 33.5% from 1997,[24] while per capita fruit and meat consumption has grown significantly, reaching 58.6kg and 60.3kg in 2019, respectively, an increase of 90% and 190%.[25] The sector will face greater challenges to decarbonize because of an expected rise in demand for animal-based products.[26]

Due to industrialization and urbanization in China, labour, land and other important agricultural inputs have become increasingly expensive. Combined with the small scale of agriculture and the changing structure of rural populations, this has resulted in higher production costs for Chinese bulk agricultural products than for major exporters like the United States, Canada, and Australia.[27] Rice, wheat, and corn prices reached US$398.6/ton, US$330.9/ton, and US$334.9/ton, respectively, in 2020, 19.1%, 78.3%, and 102.2% higher than international prices. As a result of price differences, agricultural imports have increased beyond the normal demand and production gap, leading to the importation of "non-essential" food.[28] From 2001 to 2020, China's imports of broad grains, including soybeans, increased by about 7.2 times, from 17.38 million tons to 142.55 million tons. A market-driven increase in "non-essential" agricultural imports does not necessarily reduce domestic environmental pressures on agricultural development, but it negatively impacts China's agricultural industry and threatens the employment and income of farmers.[29]

China's agricultural success has come at a price. Its agricultural emissions grew by 37.2%, from 605 $MtCO_2eq$ per yr in 1994 to 830 $MtCO_2eq$ in 2014 and now account for 13% of global agriculture-related GHG emissions.[30,31] However, the contribution of the agriculture sector to total national emissions has declined, from 18.7% to 7.5%, as total emissions across sectors in China have increased even more. Whereas agriculture emits GHGs, the LULUCF sector presents a net sink in China (Figure 2). Rapid afforestation has seen the LULUCF sinks increase from sequestering 407 $MtCO_2eq$ per year in 1994 to 1,115 $MtCO_2eq$ in 2014 (the most recent year for which official data is available). Among the emissions from agricultural sources, enteric fermentation from ruminants was the largest source of methane (CH_4) emissions and agricultural soils were the largest source of nitrous oxide (N_2O) emissions. In 2014, GHG emissions from enteric fermentation, manure management, rice cultivation, agricultural soils, and field burning of agricultural residues were 207 $MtCO_2eq$, 139 $MtCO_2eq$, 187 $MtCO_2eq$, 288 $MtCO_2eq$ and 9 $MtCO_2eq$ respectively, accounting for 24.9%, 16.7%, 22.5%, 34.7% and 1.1% of total emissions from agricultural sources.

Figure 2: Composition of AFOLU GHG emissions and removals for China in 2010 and 2014

Data source: Government of China, 2018[32]; Government of China, 2016[33]; Government of China, 2018.[34]

3. Methods and data

To ensure a systematic and uniform review of existing GHG projections for the Chinese AFOLU sector and the models being used to develop them, researchers from the International Institute for Applied Systems Analysis (IIASA) and Renmin University of China developed two standardized reporting templates. These reporting templates were developed such that the key features of Chinese models and GHG projections could be collected in a standardized manner.

The "modelling features template" focused mainly on the critical features of the models themselves. It aimed to improve our understanding of how differences in these features influence projections. The template included aspects such as the coverage of pools and gases, representation of land use categories, accountability of land use conversions, and regional and sectoral coverage of the model.

The "projections template" aimed to improve our understanding of existing projections. The template allowed the project partners to report on projections from 2010 to 2100 for crucial variables such as land use transitions, developments of pools and gases, food and feed production, and other indicators such as food security (where included in the model).

To facilitate smooth and correct inclusion of data in the reporting templates and thereby ensure high-quality analysis of the critical features of the models, both included extensive instructions and pre-filled examples. Once developed, the two templates were circulated to the project partners to validate and clarify any uncertainties. All project partners assisted with this work and provided valuable insights and ideas to improve the templates.

Once the reporting templates were finalised and tested, we reached out to the 10 key modelling teams working within and outside China for their input, either focusing on a specific AFOLU sub-sector, a full AFOLU sector or on AFOLU as part of integrated assessment models. Ten key modelling teams were selected based on a mapping of the existing modelling landscape in China, with a focus on those with documented projections for the Chinese AFOLU sector. However, this report only includes models that provide national coverage for China and projections of GHG emissions and removals to 2050/2060 (reporting years varied across the models). This comparison therefore assesses a total of eight models: GLOBIOM-China, MAgPIE-China, GCAM5.3, FABLE Calculator-China, ORCHIDEE, PECE-LIU, AGHG-INV and SRNM. Other potential candidates, such as DNDC, APSIM, and CENTURY/DayCent, have not been included in this assessment as no projections could be provided in time for this study. The reporting templates were circulated to all modelling teams by September 2021. After that, we interacted directly with each modelling team to provide clarifications and further explanations on how to reflect the specifics of their model assumptions in the two reporting templates.

All eight modelling teams filled in and reported on the modelling feature template, and five modelling teams submitted the projection template. It should be noted that the modelling teams submitted their individual latest projections for this assessment, thus no harmonization has been performed between the modelling teams in terms of underlying data sources (e.g., emission coefficients, land use, mitigation options) or key drivers for their projections (e.g., social economic development, climate change, international trade, national/international policies). Further information about the individual models can be found in Annex I.

4. How do the models compare in their coverage?

4.1. System boundaries and coverage of land use categories

Based on the information received from the modelling teams, we made a preliminary assessment of the current state of modelling capacities for China (Table 1). In this section we first discuss the coverage of the models that include the LULUCF sector (GLOBIOM-China, MAgPIE-China, GCAM5.3, FABLE Calculator-China, ORCHIDEE and PECE-LIU), and then focus on the models that cover the agriculture sector (GLOBIOM-China, MAgPIE-China, GCAM5.3, FABLE Calculator-China, AGHG-INV and SRNM).

Six models cover all or parts of the LULUCF sector, with a focus on forest land, cropland, grassland and 'other land' (Table 2).[iii] According to the Chinese National GHG Inventory of 2014,[35] these four land use types account for 90% (675.29 Mha) of China's total land area. All these models account for developments for forest land, with only one model (PECE-LIU) not accounting for cropland or grassland. As many as four models (GLOBIOM-China, MAgPIE-China, GCAM5.3 and FABLE Calculator-China) also account for developments on other land (73.63 Mha). However, a low level of attention has been paid to wetlands (39.73 Mha) and settlements (37.23 Mha). Of the models reviewed, only MAgPIE-China includes wetlands, and only GCAM5.3 and the FABLE Calculator-China models account for settlements.[iv]

Of the six models that include forest land, three distinguish between managed and unmanaged forest land. Of the five models that include grassland, two distinguish between managed and unmanaged grassland. MAgPIE-China, the only model that considers wetlands, also distinguishes between managed and unmanaged wetlands. No information could be retrieved from the Chinese National GHG Inventory of 2014 on the split between managed and unmanaged land for the different land use categories.

Thus, the existing models vary in their scope and their representation of key features of China's major land uses and agriculture sector. In addition, none of the models that cover the LULUCF sector cover all land use types.

iii. According to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, 'other land' includes bare soil, rock, ice, and all land areas that do not fall into any of the other five main land use categories, i.e., forest land, cropland, agriculture, grassland, and settlements.

iv. Settlements are treated as static in MAgPIE-China.

Table 1. Comparison of main model features						
Model name	**AFOLU sectoral coverage**	**Methodology**	**Geographical coverage**	**Purpose**	**First year of projections**	**Time horizon and time steps**
GLOBIUM-China	Agriculture & LULUCF	Partial equilibrium model	Multi-region	Forecasting	2010	Long-term, every 10 years until 2100
MAgPIE-China	Agriculture & LULUCF	Partial equilibrium model	Multi-region	Forecasting	2010	Long-term, every 5 years until 2100
GCAM5.3	Agriculture & LULUCF	Partial equilibrium model	Multi-region	Forecasting	2015	Long-term, every 5 years until 2100
FABLE Calculator-China	Agriculture & LUC*	Equilibrium model without optimisation	National	Forecasting, policy simulation	2000	Long-term, every 5 years until 2050
ORCHIDEE	LULUCF	Process-based model	Multi-region	Forecasting, back-casting, policy simulation	2015**	Long-term, every year until 2100/2300
PECE-LIU	Forest sector	Optimization model	National	Forecasting	2010	Long-term, every 5 years until 2060
AGHG-INV	Agriculture	Inventory	National	Forecasting	2018	Long-term, every year until 2050
SRNM	Cropping system	Statistical model	National	Back-casting	2017	Long-term

*The FABLE Calculator-China model accounts for land-use change (LUC) but not does not account for GHG fluxes related to existing land use or forest management.

**For the ORCHIDEE model this varies between scenarios; however, for CMIP6 the future climate starts from 2015.

Table 2. Comparison of models' land-use coverage and land area estimates for China (2014)

Data/Model	2014 land area estimates (Mha)[36]	GLOBIOM-China	MAgPIE-China	GCAM5.3	FABLE Calculator-China*	ORCHIDEE	PECE-LIU
Forest land total (i.e., managed + unmanaged)	180.04**	×	×	×	×	×	×
Forest land (managed)		×	×	×			
Forest land (unmanaged)		×	×	×			
Cropland	135.06	×	×	×	×	×	
Grassland total (i.e., managed + unmanaged)	286.56		×	×		×	
Grassland (managed)		×		×	×	×	
Grassland (unmanaged)				×		×	
Wetlands total (i.e., managed + unmanaged)	39.73		×				
Wetlands (managed)			×				
Wetlands (unmanaged)			×				
Settlements	37.23			×	×		
Other land	73.63**	×	×	×	×		

*In the FABLE Calculator-China, emissions from grassland conversion to cropland and emissions/sequestration from cropland conversion to grassland have not been included so far. However, carbon sequestration occurring on abandoned agricultural land is accounted for.

**Based on the information provided in the 2014 National GHG Inventory, forest land has been calculated as the sum of high, bamboo and open forests. 'Other land' has been calculated as shrub land.

4.2. Coverage of LULUCF pools

As the coverage of greenhouse gases and the methods used to estimate the size of emissions and removals vary between models, it is important to identify the coverage of each of the different land use models. For the six models that cover all or parts of the LULUCF sector, we assessed their coverage of carbon pools for the different land use categories, as well as the IPCC tier methods[v] that were used to calculate the development for each pool (Table 3).

We find that the carbon pools associated with forest land (including forest land, remaining forest land and land converted to forest land) have received a high level of attention by the different modelling teams (Table 3). In contrast, to date, far less attention has been paid to carbon pools associated with wetlands, settlements, other land, and harvested wood products (HWP). In terms of soil carbon pools, the models have paid more attention to representing mineral soils than organic soils. Of the six models that cover the land use sector, only two (ORCHIDEE and GCAM5.3) report that they account for the emissions by source and removals by sinks for CH_4 and N_2O for the LULUCF sector (Table 3).

Large variation can be noted in the IPCC tier methods used by the different models to calculate the development of specific carbon pools (Table 3). However, there are some patterns in the methods being applied. For example, Tier 3 methods are predominantly used for calculating carbon pools related to forest land. For carbon stock changes in living biomass, all but one model applies Tier 3 methods. The only exception is the FABLE Calculator-China, which uses a Tier 2 method for carbon pools on afforested land and abandoned agricultural land (changes in living biomass in managed forests are not accounted for). In terms of carbon stock changes in deadwood, litter, and dead organic matter, the four models that represent these pools use Tier 3 methods.

For carbon pools in wetlands and settlements, Tier 1 and Tier 2 methods are predominantly used. Tier 1 and Tier 2 methods are also predominantly used for soil carbon pools. The only exception is the ORCHIDEE model, which applies a Tier 3 method for soil carbon pools in forest land, cropland and grassland.

v. Methods used to estimate GHG fluxes are usually categorized into three tiers based on the IPCC methodology (2006, 2019), with a tier generally representing a level of methodological complexity. Tier 1 is the basic method, frequently using IPCC-recommended default values, while Tier 2 applies country-specific emission factors. Tier 3 estimates are more demanding in terms of complexity and data requirements. Tiers 2 and 3 are sometimes referred to as higher tier methods and are generally considered to be more accurate, as long as adequate data are available to develop, evaluate and apply them.

Table 3. Models' coverage of carbon pools and use of tier methods (T1, T2 or T3) to calculate changes

Land use represented in the mode	Carbon stock change in living biomass per area			Net carbon stock change in dead wood per area	Net carbon stock change in litter per area	Net carbon stock change in dead organic matter per area	Net carbon stock change in soils per area	
	Gains	Losses	Net change				Mineral soils	Organic soils
Forest land	O	O	O,P	O	O	NA	O	O
Forest land remaining forest land	GC GL,M	GC GL,M	GC GL,M	GL,M	GL,M	NA	GC	GC
Land converted to forest land	GC GL,M	GC GL,M	GC F GL,M	GL,M	GL,M	NA	GL,M GC	M GC
Cropland	O	O	O	NA	NA	O	O	O
Cropland remaining cropland	GC	GC	GC	NA	NA	NC	GC	GC
Land converted to cropland	GC	GC M	F GC	NA	NA	NC	GL,M GC	M GC
Grassland	O	O	O	NA	NA	O	O	O
Grassland remaining grassland	GC	GC	GC	NA	NA	NC	GC	GC
Land converted to grassland	GC M	GC M	GC F M	NA	NA	NC	GL,M GC	M GC
Wetlands	NC	NC	NC	NA	NA	NC	NC	NC
Wetlands remaining wetlands	M	M	M	NA	NA	NC	NC	NC
Land converted to wetlands	M	M	M	NA	NA	NC	M	M
Settlements	NC	NC	NC	NA	NA	NC	NC	NC
Settlements remaining settlements	GC	GC	GC	NA	NA	NC	GC	GC
Land converted to settlements	GC	GC	GC F	NA	NA	NC	GC	GC
Other land	NC	NC	NC	NA	NA	NC	NC	NC
Other land remaining other land	NA,M	NA,M	NA,M	NA	NA	NA	NA	NA
Land converted to other land	M	M	GC F M	NA	NA	NC	G	NC
Harvested wood products	O	O	O	NA	NA	NA	NA	NA

T3 T2 T1/T2 T1

Note: NA = not applicable. NC = not covered by any model. GL = GLOBIOM-China; M = MAgPIE-China; GC = GCAM5.3; F = FABLE Calculator; O = ORCHIDEE; and P = PECE-LIU. The methodological codes T1, T2 and T3 represent Tier 1, Tier 2 and Tier 3 methods respectively.

4.3. Coverage of LULUCF in models versus the National GHG Inventory

As none of the models reviewed cover all land use types, it is important to verify whether they cover the land use categories that account for the current main sources of GHG emissions and removals in China. In other words, have the models so far focused on the most important land use sectors for GHG emissions? Furthermore, are there large differences between the tier methods used for the development of China's 2014 National GHG Inventory,[37] and those used by the modelling tools?

When comparing the models' coverage with China's main sources of emissions and removals (Table 4), overall the models do provide good coverage of most of the main current sources (forest land, grassland and cropland), with the exception of harvested wood products. Only one model covers harvested wood products (ORCHIDEE), and only one model covers wetlands (MAgPIE-China), both of which are relatively large sinks and for which country-specific emissions factors for China have been developed for the national GHG inventories. Interestingly, four out of the six models cover the 'other land use' category, even though it is not of high importance in China for current GHG emissions and removals. However, including this land use category in the models does provide a more complete representation of current land use and land use transitions. Therefore, from a modelling perspective it makes sense to include this category.

Table 4. Comparison of coverage of land-use categories and CO_2 sources and sinks by the reviewed models and the Chinese 2014 National GHG Inventory

Land use category	Reviewed models		Methodologies used for the 2014 National GHG Inventory[38]		
	Coverage by models	Tier method	Tier method	Emission factors	2014 emissions and removals (kt)
Forest land	6 of 6	T1 / T2 / T3	T2	CS	-837,730
Cropland	5 of 6	T1 / T2 / T3	T3	CS	-49,460
Grassland	5 of 6	T1 / T2 / T3	T2	CS	-109,160
Wetlands	1 of 6	T1	T2	CS	-44,540
Settlements	2 of 6	T1 / T2	T2	CS	2,530
Other land	4 of 6	T1 / T2 / T3	T1	D	0
Harvested wood products	1 of 6	T1	T2	CS	-110,550

Note: The methodological codes T1, T2 and T3 represent Tier 1, Tier 2 and Tier 3 methods respectively. CS = country-specific emission factors for China; D = default IPCC emission factors. * It should be noted that no separation is being made between models that have full or partial coverage of a land-use category. For example, FABLE Calculator-China only accounts for afforested land during the timescale of the model run, not all forest land within China. See Table 2 for further information on the models' coverage of different land-use types.

4.4. Coverage of agricultural non-CO_2 emissions versus the National GHG Inventory

We collected data from six models that account for non-CO_2 emissions from the agricultural sector (GLOBIOM-China, MAgPIE-China, GCAM5.3, FABLE Calculator-China, and AGHG-INV, and SRNM). All except SRNM consider major agricultural sources for non-CO_2 greenhouse gas emissions, and there are substantial similarities across these five models (Table 5 and Table 6). They have all adopted the

IPCC inventory framework and have considered the most critical sources of non-CO_2 GHG emissions from agriculture – enteric fermentation, manure management, and rice cultivation for CH_4 emissions; and enteric fermentation, manure management, and agricultural soils for N_2O emissions. However, only AGHG-INV includes emissions from other large livestock, such as camels, horses, and mules. GLOBIOM-China does not include N_2O from the burning of agricultural residues. In addition to these five models, SRNM focuses on the variation of N_2O emissions from agricultural land with nitrogen application, and only considers N_2O emissions from agricultural soils and the partial discharge of manure (returned to the field as organic fertilizer).

Across the different models, Tier 2 is predominantly used when calculating GHG emissions from the agriculture sector. China-specific emission factors are used in all five models for all significant animal species and agricultural land types. However, IPCC defaults are often used for some less substantial sources (e.g., camels). Tier 3 methods are rarely used in this sector, particularly for models used to develop projections for the Chinese AFOLU sector. Over the past two decades, many studies have been conducted in China to monitor and evaluate the emission factors for rice cultivation, different types of drylands, and livestock and poultry breeding activities, which have laid a relatively good foundation for modelling studies. While some Tier 3 inventory studies have been conducted in China for rice cultivation and agricultural soils, they unfortunately encountered difficulties in conducting long-term emission scenario analyses.[39]

Table 5. Comparison of CH_4 sources and sink categories in the reviewed models and China's 2014 National GHG Inventory

Activity category	Reviewed models		Methodologies used for the 2014 National GHG Inventory[40]		
	Model coverage	Tier method	Tier method	Emission factors	2014 emissions (kt)
Enteric fermentation	5 of 6	Mainly T1 / T2 Partly T3	T2	D, CS	9,856
Manure management	5 of 6	T1 / T2	T2	D, CS	3,155
Rice cultivation	5 of 6	T1/T2/T3	T3	CS	8,911
Agricultural soils	5 of 6	NA	NA	NA	NA
Field burning of agricultural residues	4 of 6	T1	T1	D, CS	323

Note: The methodological codes T1, T2, and T3 represent Tier 1, Tier 2, and Tier 3 methods. CS = country-specific emission factors for China; D = default IPCC emission factors; NA = not applicable.

Table 6. Comparison of N_2O sources and sink categories in the reviewed models and China's National 2014 GHG Inventory

Activity category	Reviewed models		Methodologies used for the 2014 National GHG Inventory[41]		
	Model coverage	Tier method	Tier method	Emission factors	2014 emissions (kt)
Manure management	6 of 6	T1/T2	T2	D, CS	233
Agricultural soils	6 of 6	T1 / T2	T2	D, CS	930
Field burning of agricultural residues	4 of 6	T1	T1	D, CS	7

Note: The methodological codes T1, T2, and T3 represent Tier 1, Tier 2, and Tier 3 methods. CS = country-specific emission factors for China; D = default IPCC emission factors.

5. How do the model projections compare?

5.1. Projections for the LULUCF sector

Five modelling teams submitted their existing projections for the LULUCF sector for this assessment (GLOBIOM-China, MAgPIE-China, GCAM5.3, FABLE Calculator-China and PECE-LIU). The models vary substantially both in their starting points for projections (Table 7 and Table 8), and the expected development of the LULUCF sector (Figure 3). Regarding the level of GHG emissions and removals at the starting point of the projections (which vary from 2014 to 2016), only the PECE-LIU model showcases a level of GHG emissions and removals relatively consistent with China's latest 2014 National GHG Inventory.[42] This is not surprising, as the PECE-LIU model has been calibrated against the National Forest Resources Inventory and China's National GHG Inventory data for 2006 and 2016.

The GLOBIOM-China and GCAM5.3 models both indicate that the LULUCF sector is a net sink in 2015, but the size of the sink is much smaller than estimated in China's 2014 National GHG Inventory (Figure 3, Table 7). In contrast, the MAgPIE-China and FABLE Calculator-China models both indicate that the LULUCF sector is a net source of emissions in 2015. In the case of the MAgPIE-China model this is mainly driven by the large amount of emissions from grasslands (Figure 3, Table 7). Meanwhile, the FABLE Calculator-China only represents anthropogenic emissions and removals associated with land use change, and ignores emissions and removals associated with current land use. For example, the model accounts for sequestration from reforestation/afforestation events and the build-up of carbon sequestration over time, but does not account for fluxes to and from carbon pools in forest land or remaining forest land.

Table 7. Comparison of annual GHG emission and removal estimates by the models and the 2014 National GHG Inventory ($MtCO_2eq$ per yr)

Land-use category	2014 National GHG Inventory[43]	GLOBIOM-China	MAgPIE-China	GCAM5.3	FABLE Calculator-China	PECE-LIU
Year	2014	2015	2015	2015	2015	2016
LULUCF total	-1,115.91	-312.27	133.2	-135.98	185	-934
Forest land	-837.73	-389.80	-1,396.75		-296	-934
Cropland	-49.46	77.53	-38.32		7	NC
Grassland	-109.16	0	1,346.59		460	NC
Wetlands	-44.54	NC	53.40	NC	NC	NC
Settlements	2.53	NC	NC		15	NC
Other land	0	NC	168.29		0	NC
Harvested wood products	-110.55	NC	NC	NC	NC	NC

Note: NC = not covered. This signals that the model does not include a carbon pool for that land-use category.

Table 8. Comparison of land-use area estimates in the models and the 2014 National GHG inventory (million hectares)						
Land-use category	**2014 National GHG Inventory**[44]	**GLOBIOM-China**	**MAgPIE-China**	**GCAM5.3**	**FABLE Calculator-China**	**PECE-LIU**
Year	2014	2015	2015	2015	2015	2016
Forest land	180.04*	211.92 (104.58)	200.4 (NR)	140.47 (102.06)	210.99 (177)	220.45 (0)
Cropland	135.06	148.88 (NR)	111.90 (NR)	116.00 (NR)	122.41 (122.11)	NC
Grassland	286.56	205.96 (94.57)	374.94 (NR)	551.11 (456.47)	411.85 (386.04)	NC
Wetlands	39.73	NC	3.35 (NR)	NC	NC	NC
Settlements	37.23	NC	5.99 (NR)	5.99 (NR)	5.67 (5.11)	NC
Other land	73.63*	389.29 (389.29)	229.2 (NR)	115.74 (NR)	192.31 (192.31)	NC

Note: For the model estimates, land areas are reported as total land. The figures in parentheses are the land areas assumed to remain neutral in terms of emissions and removals, i.e. there is a balance between carbon dioxide emissions emitted and absorbed carbon from the atmosphere in the area in a state of net-zero carbon dioxide emissions. NC = not covered (used when the model does not include a carbon pool for the land-use category). NR = not reported (used when the modelling team chose not to report the estimate).

*Based on the information provided in the 2014 National GHG inventory, forest land has been calculated as the sum of high, bamboo and open forests. 'Other land' has been calculated as shrub land.

Given that GCAM5.3, GLOBIOM-China and MAgPIE-China all provide good coverage of the most important land use categories for historical GHG emissions and removals (Table 2 and Table 5), and use tier methodologies that are relatively consistent with China's national GHG inventories, the difference in reported values for the period 2010-2020 between the three models and the national GHG inventories is striking. The largest differences between the models and the national GHG inventories mainly relate to the representation of forest land, harvested wood products, cropland and grassland (Table 7). According to the 2014 National GHG Inventories for China, forest land represented a net sink of -837 MtCO_2eq in 2014. However, the models' estimates for the size of the sink vary between -1,469 and -389 MtCO_2eq in 2015. As the area of forest land is relatively consistent between the models and the GHG inventories (Table 8), these discrepancies are likely to be explained by differences in the activity data, emission factors and data sources used to calculate the size of the sink (i.e., forest growth functions, representation of different tree species, current annual increment, forest age structure, managed vs. unmanaged land etc.). Furthermore, the models likely use different data sources to represent historical afforestation and deforestation trends. As an example, historical afforestation and deforestation trends in GLOBIOM-China are commonly harmonized with the FAO FRA 2020 dataset, which may differ from the data being used for the preparation of the Chinese national GHG inventories reported to the UNFCCC.

Figure 3: Historical and projected GHG emissions and removals for the LULUCF sector

Note: Projections include scenarios from GLOBIOM-China, FABLE Calculator-China, MAgPIE-China, GCAM5.3, and PECE-LIU. Details of each scenario can be found in Annex II. Historical LULUCF GHG information has been compiled from PRC National Communication 2012[45] and PRC First and Second Biennial Update Report on Climate Change in 2016[46] and 2018.[47]

In terms of the developments of net GHG emissions for the LULUCF sector, the GLOBIOM-China, FABLE Calculator-China and MAgPIE-China models all expect a decrease of net GHG emissions and a long-term increase in the removals for LULUCF sector (i.e., by 2050/2060 as compared to 2000/2010): the expected reductions of net GHG emissions range from 109 $MtCO_2eq$ for MAgPIE-China, 206 $MtCO_2eq$ for GLOBIOM-China and 266 $MtCO_2eq$ for the FABLE Calculator-China (Figure 3). The GCAM5.3 and PECE-LIU models project the LULUCF sector to remain a carbon sink overall, albeit with a slight sink reduction (between 34 and 120 $MtCO_2eq$ by 2060) compared to current levels. The difference in projections may relate to differences between the scenarios in terms of drivers of change, but also fundamental differences in model types, given the broad range of models being used.

What is also striking in the projections for the LULUCF sector is that while the GLOBIOM-China, GCAM5.3 and MAgPIE-China models envisage a relatively smooth development of the LULUCF sink, the FABLE Calculator-China and the PECE-LIU models project strong fluctuations in the net emissions over time (Figure 3). PECE-LIU predicts a decline in LULUCF carbon sinks between 2016 and 2025, due to a reduction in the forest carbon stock growth rate and a decrease in the national afforestation rate. Note that in contrast to the other model projections, the PECE-LIU model projection incorporates China's latest land use and policy targets and assumes they will all be met.[vi] The scenario predicts that fulfilling these targets will result in a reduction in the forest stock growth rate between 2016 and 2025 (compared to the previous reporting period), which will subsequently reduce forests' carbon sink role by a substantial amount. In addition, the pace of afforestation in China is expected to slow down as the most suitable areas are already afforested, leading to future afforestation efforts shifting to more challenging areas within the country.

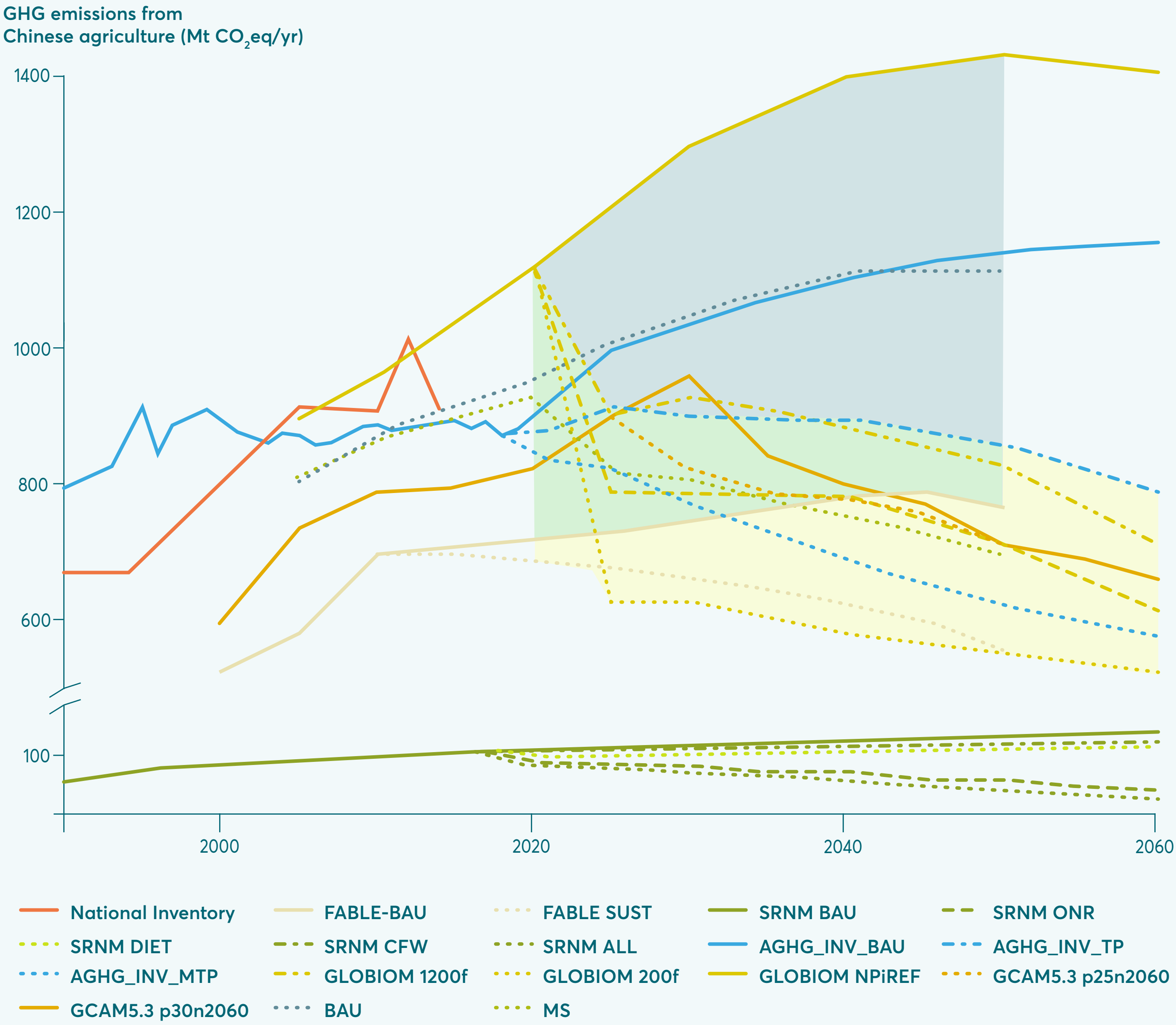
5.2. Projections for the agriculture sector

Based on the Chinese National GHG Inventory and model results (Figure 4), the agricultural sector produced 638 MtCO_2eq of non-CO_2 greenhouse gas emissions in 2000, and in 2020 these emissions increased to 950 MtCO_2eq, ranging between 711 MtCO_2eq and 1,118 MtCO_2eq. The uncertainty range for non-CO_2 GHG emissions is about 50% for the base year, and most models provided results from 2000 to 2050. In the SRNM estimates, only emissions from crop farming activities are included, so the results are a fraction of the other model estimates. However, they appear robust for that sub-category and are within 12% error of the national inventory and AGHG-INV models' estimates of crop farming emissions (including rice cultivation and agricultural soils).

In the business-as-usual (BAU) scenarios, most models project the non-CO_2 emissions from China's agricultural sector to increase at a more moderate rate after 2030, and to peak between 2045 and 2060. The peak emission projections range from 760 MtCO_2eq (FABLE-calculator) to 1,434 MtCO_2eq (GLOBIOM-China) (Figure 4). These differences are explained by differences in base years, model structure, scenario assumptions, and parameter selection. The maximum mitigation potential averaged 400 MtCO_2e per year (200 to 800 MtCO_2eq) in 2050 across the models. The most optimistic mitigation estimation is from the GLOBIOM-China model, with a range of between 600 MtCO_2eq and 900 MtCO_2eq by 2050, in part reflecting its highest BAU emission (1,434 MtCO_2eq in 2050). GCAM does not report a BAU scenario, but instead models two trajectories of China's agricultural GHG emissions under two different scenarios whereby national total greenhouse gas emissions peak in 2025 and in 2030. In the 2030-peaking scenario, China's agricultural GHG emissions are projected to peak at 957 MtCO_2eq, whereas in the 2025-peaking scenario, they would peak at 895 MtCO_2eq and then decline, with peak emissions 7% lower. The emissions in 2060, however, are quite similar for the two GCAM scenarios, at about 653 MtCO_2eq.

vi. Its projections are based on two main documents: one published by the Communist Party of China Central Committee and the State Council (2021) covering the period 2025 to 2030, and the other by the National Forestry and Grassland Administration (2019), covering 2035 to 2050. These include targets for the forest cover rate to reach 24.1% (ca. 230 million hectares) and forest stock volume to reach 19 billion cubic metres.

Figure 4: Historical and projected non-CO_2 GHG emissions from China's agriculture, 1990-2060



Note: Projections include scenarios from GLOBIOM-China, GCAM5.3, FABLE Calculator-China, AGHG-INV and SRNM (for agricultural N_2O emissions only). Historical agricultural GHG information has been compiled from the PRC National Communication 2012[48] and PRC First and Second Biennial Update Report on Climate Change in 2016[49] and 2018[50]. Details of each scenario can be found in Annex II. Shaded areas represent the mitigation potential as estimated by the different models. BAU and MS are the average across business as usual (BAU) projections and all mitigation scenarios (MS), but note that SRNM is not included in the calculation due to its partial coverage.

6. Knowledge gaps and recommendations to improve models

This assessment highlights significant uncertainties in existing model projections for historical and future LULUCF-related emissions and removals for China. The difference in historical net emissions between the models is striking (1,119 $MtCO_2eq$, Figure 3). This uncertainty level is equivalent to the estimated size of the national GHG sink for China in 2014 (1,150 $MtCO_2eq$). A certain amount of variation between the models can be explained by the differences in scope, structure, input data, land use coverage, carbon pool coverage, activity data, and emission factors. There is still a lot of progress to be made in harmonizing and improving the models in order to align them better with the Chinese National GHG Inventory. Harmonization is an issue for numerous countries around the world, as noted and highlighted in the scientific literature.[51] As a recommendation, as all countries will use the new common reporting tables (CRTs) to report their national GHG inventories no later than 2024, new routines and methodologies to harmonize their baselines and projections with the CRTs need to be developed.

This review of the land use models for China reveals that a substantial number of them cover to some degree the categories of forest land (6 out of 6), cropland (5 out of 6), and grassland (5 out of 6) which are crucial for representing current levels of LULUCF emissions and related potential abatement, as seen from the Chinese National GHG Inventory of 2014.[52] Nevertheless, there are limitations in their coverage. For example, only one model covers the harvested wood products carbon pool, which currently represents the second largest sink in the Chinese National GHG Inventory (-110.55 $MtCO_2eq$). Furthermore, only two models currently cover settlements and only one covers wetlands. While neither of these land use categories currently represent significant sources of anthropogenic emissions and removals for the LULUCF sector in the Chinese National GHG Inventory, a considerable body of current literature points to their high mitigation potential and multiple co-benefits through activities such as protecting and restoring wetlands[53] and developing green urban infrastructure.[54,55] The inclusion of these land use categories and associated mitigation potentials in the different modelling tools would therefore be advantageous.

Compared with other sectors, the LULUCF sector has a relatively high level of uncertainty surrounding estimates of anthropogenic GHG emissions.[56,57,58] For example, in China's 2014 Inventory, the uncertainty levels for the various sectors were as follows: energy ~5.2%; industrial process ~3.9%; agriculture ~19.8%; LULUCF ~21.2%, and waste ~23.2%.[59] However, previous assessments have highlighted that methodological developments could significantly help to reduce the uncertainty levels for LULUCF estimates,[60,61] including methods to identify areas of high priority for improvement.[62] Countries seeking to enhance LULUCF GHG estimation methodologies can benefit from existing research and data collection to improve models where the uncertainty levels are highest.

Based on our assessment, we highlight the following priority actions for improving modelling of the Chinese AFOLU sector:

- **Increase collaboration in model development:** Greater collaboration between model developers and national GHG inventory compilers would help to refine the data underlying the projections of future anthropogenic GHG emissions. Inter-model comparison, model validation, and collaborative efforts provide opportunities to reduce uncertainty and improve projections. Cross-sectoral comparisons in the AFOLU sector require more work, in particular reconciling models' inconsistencies, harmonizing BAU assumptions and mitigation scenarios, as well as including estimates of the potential impact of policies related to the sector.

- **Share and make data open access:** Shared data sources are key for improving the calibration of models and reducing model uncertainty. By making datasets on emission factors and activities for the Chinese National GHG Inventory and by the different modelling teams freely available, not only will the calibrating of the models be enhanced, but the results of the models themselves will also be more transparent.

- **Enable multi-model comparisons:** Making detailed projections public, along with systematic mechanisms to compare different models and studies, will allow national and international stakeholders to better understand mitigation pathways, gain confidence in modelling results, and incorporate these findings into policymaking.

Furthermore, for the development of technically feasible 1.5°C compatible emission pathways for the AFOLU sector, and to develop pathways for the sector that are aligned with China's net neutrality target and the Paris Agreement, we urge policy makers to fund research activities that:

- **Target the most uncertain areas:** High uncertainty estimates for the AFOLU sector may reduce international confidence in emission reduction claims, especially for countries that expect forests and agriculture to contribute significantly to near-term reductions of GHG emissions.

- **Include additional mitigation options and sectors with large-scale abatement potential:** Further efforts to include neglected sectors (such as wetlands and settlements) in the various modelling tools can help eliminate many of the differences between models and thus allow for a more accurate assessment of future emissions in the AFOLU sector. Moreover, by incorporating low-cost but high-potential mitigation options into the various modelling frameworks, models can consider a more comprehensive set of mitigation options and help policy makers create more holistic mitigation pathways.

Annex I: Model descriptions

GLOBIOM-China

The Global Biosphere Management Model (GLOBIOM) is a recursive dynamic,[vii] spatially explicit, economic partial equilibrium model of the agriculture, forestry, and bioenergy sector with bilateral trade flows and costs.[63] The model is built following a bottom-up setting based on detailed grid-cell information, providing the biophysical and technical cost information. The model computes a market equilibrium in 10-year time steps from 2000 to 2100 by maximising welfare (the sum of consumer and producer surplus) subject to technological, resource, and political constraints. In each step, market prices adjust endogenously to equalise supply and demand for each product and region. GLOBIOM-China was further developed with an enhanced representation of China's agricultural sector and environmental dynamics, a detailed validation, and confined assumptions following existing policies in China.[64]

MAgPIE-China

The Model of Agricultural Production and its Impact on the Environment (MAgPIE)[65,66,67,68] is a global agro-economic land system model which is connected to the grid-based dynamic vegetation model LPJmL,[69,70] with a spatial resolution of 0.5° x 0.5°. MAgPIE contains 12 world regions, in which countries are grouped together according to their geo-economic conditions.[71] The model is run in a recursive dynamic mode over five-year intervals from 1995 to 2100. Agricultural production is endogenously determined in the optimisation, where the total cost of production is minimised for a given amount of regional food and bioenergy demand. The regional food demand is mainly driven by population and income growth. It takes into account regional economic conditions such as demand for agricultural commodities, technological development, and production costs, and spatially explicit data on potential crop yields land and water constraints. Based on these, the model derives spatially explicit land use patterns, yields, and total agricultural production costs for each grid cell. MAgPIE-China has been further developed to incorporate existing agriculture and environmental-related polices in China to improve the representation of China's AFOLU sector.[72]

GCAM5.3

The Global Change Analysis Model (GCAM) is an integrated tool for exploring the dynamics of the coupled human-Earth system and the response of this system to global changes.[73,74] GCAM is a worldwide model representing the behaviour of and interactions between five systems: energy; water, agriculture, and land use; the economy, and the climate. Its energy-economy system currently operates for 32 regions globally, the land is divided into more than 300 subregions, and water is tracked for 233 basins. GCAM5.3's core operating principle is market equilibrium, and the representative agents in GCAM5.3 use the information on prices to interact with each other and make decisions about the allocation of resources. In GCAM5.3, modules on agriculture and land systems provide information about land use, land cover, carbon stocks and net emissions, the production of bioenergy, food, fibre, and forest products. Their demands are driven by the size of the population, their income levels, and commodity prices, and from these, land and GHG emissions are derived.[75] The demand for bioenergy is driven by the energy sector, and agriculture and land systems module demand from water systems.

vii. The "recursive dynamic" and "forward-looking dynamic" terminology refers to the solution approach of the model but it also implies different representations of the expectations of economic actors. In a recursive model, decisions about production, consumption and investment are made only on the basis of prices in the period of the decision, and this is often referred to as "myopic" expectations. Decisions are thus made as if costs and prices will remain unchanged in the future. In a forward-looking model, decisions today are being optimized over the full horizon, meaning that decisions today about production and consumption are based on expectations that are realized in the model simulation. Thus, economic actors are characterized as having "perfect" foresight — they know exactly what will happen in the future in all periods of time covered by a modeling exercise.

FABLE Calculator-China

The Food, Agriculture, Biodiversity, Land use, and Energy (FABLE) Calculator is written in Excel and solved by ensuring equilibrium between the various uses (food, feed, processing) and domestic production minus exports plus imports, under a land availability constraint, for each five-year period over 2000-2050.[76] It focuses on agriculture as the primary driver of land use change. It tests the impact of different policies and changes in the drivers of these systems through the combination of many scenarios, including population growth, dietary change, productivity growth, trade, loss and waste, climate change impacts, etc. It includes 76 raw and processed agricultural products from the crop and livestock sectors and relies extensively on the FAOSTAT (2022) database for input data. For every five-year interval over the period 2000-2050, the Calculator computes the level of agricultural activity, land use change, food consumption, trade, greenhouse gas emissions, water use, and biodiversity conservation. Market balance, agricultural land use and agricultural emissions are calibrated for the years 2000, 2005 and 2010 using FAO statistics. The model is a national model in that it only represents development for China and has been modified to reflect the Chinese context, e.g. China's Cropland Protection Redline, China's target to achieve 26% forest cover rate by 2050, and historical changes in animal feed composition.[77]

ORCHIDEE

ORCHIDEE (Organising Carbon and Hydrology In Dynamic Ecosystems) is the process-based land surface model of the French Institut Pierre Simon Laplace (IPSL), built for simulating carbon cycling in terrestrial ecosystems, and water and energy fluxes from site to global scale.[78] The model can be driven by observation-based climate forcings, land cover and land use change maps (vegetation is presented as a series of plant functional types), and can potentially account for a series of natural and anthropogenic factors, such as fire,[79] crops,[80] grassland management,[81,82] forest management,[83] and bioenergy crops.[84] ORCHIDEE is widely used for simulating global carbon, water and energy fluxes over terrestrial ecosystems and is one of the land models used for the annual Global Carbon Budget. The modelled carbon and water and energy dynamics (storage and fluxes) have been widely calibrated (for its parameters) and validated against various earth observations from site to global level,[85] and from field measurement to remote sensing observations, sometimes with data assimilation systems (ORCHIDAS; https://orchidas.lsce.ipsl.fr/). For future emissions from the AFOLU sector, the model can be driven by projections of climate from global climate models (GCMs) (e.g., those in CMIP6) and projections of land use change (e.g., crop/pasture expansion from integrated assessment models, IAMs), and can simulate future global terrestrial carbon cycles under different scenarios.

The ORCHIDEE model is designed to be coupled to a global circulation model (such as LMDz within the IPSL-CM earth system model framework).[86] It is set up so that atmospheric conditions affect the land surface processes, and the land surfaces in turn feed back to atmospheric conditions through changes in carbon, water and energy fluxes. Coupled land-atmosphere models thus offer the possibility of quantifying the climate effects of changes on the land surface and the impact of climate change on the land surface.

ORCHIDEE has been calibrated and validated for terrestrial ecosystems in China, and used for assessing carbon, water, and energy fluxes.[87,88,89,90,91,92,93]

PECE-LIU Model

The Program of Energy and Climate Economics energy system model (PECE-LIU) is a bottom-up national energy-economy-environment system model with abundant technology details, of which the LULUCF module is focused on forest carbon sink estimation.[94,95] The module is constructed based on the Stock-Difference method and the forestry carbon sink estimation framework from IPCC, which applies field forestry resources inventory data to calculate the national forest carbon pool and year-to-year changes, calibrated against the National Forest Resources Inventory and GHG Inventory data between 2006 and 2016. The model quantitatively simulates the development potential of forest carbon sinks in China from 2016 to 2060 with a policy-driven approach, using the near-term plan (e.g. the 14th Five-year plan), the carbon peaking and carbon neutral targets as important drivers to estimate future carbon sink development. The LULUCF module is further integrated with other modules of PECE-LIU to harmonize the dynamics of carbon sources and sinks in support of China's long-term low-carbon transition pathways.

AGHG-INV

The Agriculture-induced non-CO_2 GHG INVentory model (AGHG-INV) is a bottom-up model[viii] with technology details.[96,97] It can provide projections of non-CO_2 GHG emissions from agricultural sources at the provincial level and is built on publicly available activity data from the national statistical database and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.[98] In AGHG-INV, activity drivers for emission projections enter calculations externally using scenario data from different internationally and nationally recognised sources. Emission factors are consistent with historical levels in a business-as-usual (BAU) scenario, and emissions are a function of the projected activity level of major agricultural activities which reacts to animal feeding and crop farming, changed with national population size, urbanisation, economic development, and per capita consumption of major food products. The technical potential (TP) scenario evaluates the physical abatement potential of current best available technologies or practices, showing a conventional technology development path. The maximum technical potential (MTP) scenario evaluates the upper limit of physical mitigation for the Chinese agricultural sector without considering any technical, economic, or social implementation barriers across regions.

SRNM

The Spatially Referenced Nonlinear Model (SRNM) is a global bottom-up model that simulates the variations in N_2O emissions from agricultural land with nitrogen application (including synthetic fertilizer, livestock manure and crop residues) under various environmental conditions and agricultural management practices.[99] Based on biogeochemistry, it assumes that the emission factor (EF) of N_2O from agricultural land is a linear function of the applied nitrogen (N) rate, i.e. the EF-N relationship. In recent calculations, it assumes that there is a quadratic relationship between the applied nitrogen rate and EFs, by using the Bayesian Recursive Regression Tree Model.[100] SRNM is driven by many input databases, including climate, soil properties, N inputs, irrigation use and the historic distribution of croplands. It can therefore capture the spatial heterogeneity of parameters such as climate, soil characteristics and crop management practices.[101] The model is calibrated with N_2O measurements from 153 peer-reviewed field studies in China, and validated by independent observations with chamber-based N_2O flux observations from 180 global distributed sites outside China.[102,103]

viii. A top-down approach looks at the system under examination as a whole and uses reduced form behavioural relationships with econometrical validation, while bottom-up approaches are developed from an engineering perspective and start from the sector of interest in detail before expanding the focus onto the whole system.

Annex II: Data and scenario interpretation for Figure 4

Annex. Data and scenario interpretation for Figure 4

Abbreviation	Descriptions
National Inventory	Official data from national inventory, only for 1994, 2000, 2005, 2010, 2014
FABLE BAU	BAU scenario for FABLE Calculator-China. It is characterized by a moderate population decrease, no constraints on agricultural expansion, a high afforestation target, medium productivity increases in the agricultural sector, an evolution towards higher consumption of animal products, and low livestock productivity increases.
FABLE SUST	Sustainable Pathway represents a future in which significant efforts are made to adopt sustainable policies and practices and corresponds to a high boundary of feasible action compared to the Current Trends.
SRNM BAU	In the business as usual (BAU) scenario, current (the year 2017) policies and national plans were considered without any further policy interventions. To feed the growing population, crop production, sowing area and N input were predicted to increase. However, yield and agricultural management (including N rate, fertilizer types, fertilizer application methods, tillage and irrigation methods) were kept the same as in 2017, and climate factors changed with future climate scenario (RCP2.6) provided by the Inter-Sectoral Impact Model Intercomparison Project.
SRNM ONR	Optimizing N fertilizer rate (ONR) scenario assumed the projections to be the same as BAU, except the total N input and N rate will dramatically decrease to improve agricultural N use efficiency and control N pollution.
SRNM DIET	Changing dietary guidelines (DIET) scenario, all projections were assumed to be the same as BAU, while the crop production would shift to optimizing human dietary structure. The DIET scenario assumes that the corresponding demand of maize for animal feed would reduce by 16-34%, which is in accordance with Chinese dietary guidelines.
SRNM CFW	All input data in cutting food waste (CFW) scenario were the same as BAU, but crop production was assumed to decline in order to achieve the UN Global Sustainable Development Goals, driven by the reduced 50% food loss and waste in 2030, 2040 and 2050 compared with 2017.
SRNM ALL	ALL scenario was a package of ONR, DIET and CFW, which assumed that N inputs and N rate were the same as those in ONR scenario, meanwhile crop production met the projections of scenarios DIET and CFW.
AGHG_INV BAU	In BAU, 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.
AGHG_INV TP	The technical potential (TP) scenario evaluates the physical abatement potential of current best available technologies or practices, showing a conventional technology development path.
AGHG_INV MTP	Maximum Technical Potential (MTP) scenario evaluates the upper limit of physical mitigation for the Chinese agricultural sector, without the consideration of any technical, economic or social barriers of implementation across regions.
GLOBIOM 1200f	Carbon Budget: 1200 Gt CO_2, Budget schemes: Full-century budget
GLOBIOM 200f	Carbon Budget: 200 Gt CO_2, Budget schemes: Full-century budget
GLOBIOM 700f	Carbon Budget: 700 Gt CO_2, Budget schemes: Full-century budget
GLOBIOM NPiREF	GLOBIOM-China BAU scenario
GCAM5.3 p25n2060	CO_2 emissions peak in 2025, and GHG emissions reach net zero in 2060
GCAM5.3 p30n2060	CO2 emissions peak in 2030, and GHG emissions reach net zero in 2060

Note: FABLE: The Food, Agriculture, Biodiversity, Land-use, and Energy Calculator
GCAM5.3: Global Change Analysis Model
GLOBIOM-China: Global Biosphere Management Model
AGHG-INV: Agriculture-induced non-CO_2 GHG INVentory model
SRNM: Spatially Referenced Nonlinear Model

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Gaps and recommendations

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