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

Supplementary Information

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## S1 Detailed model description

"Bottom-up" and "Top-down" are the two modeling paradigms to present interactions between the focus sector and the economy (Barker et al., 2007; Bohringer and Rutherford, 2006; Kolstad et al., 2014). The top-down approach examines the broader economy and represents economic agents in an aggregate manner. They can incorporate feedback effects between different markets triggered by policy-induced changes on relative prices and incomes and then analyze the policies' impact on economic growth, trade, employment, and public revenues (Bohringer and Rutherford, 2006; Timilsina et al., 2021). The bottom-up models usually refer to sectoral-based or technology-based models, which simulate the interactions among various individual technologies within a sector or a sub-system of the economy (Bohringer and Rutherford, 2006; Wing et al., 2008). They can provide detailed physical and economic representations of supply- and demand-side technology paths.

The ***A***griculture-induced non-CO2 ***GHG*** ***INV***entory model (AGHG-INV) is a bottom-up model, and it follows the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). This model is built upon publicly available activity data from the national statistical database (<http://https--data--stats--gov--cn--e4192.proxy.www.stats.gov.cn/easyquery.htm?cn=C01>).

Primary non-CO2 GHG sources in AGHG-INV include enteric fermentation during the production of ruminants (including cattle, sheep, and goats), which emits CH4; livestock manure, which emits N2O and CH4; production of rice in paddy fields, which emits CH4; direct N2O emission from agricultural soils due to human-induced net nitrogen additions to the ground via chemical fertilizers and organic fertilizer, as well as indirect N2O emission through deposition, leaching, and runoff; and combustion of agricultural residues, which emits N2O and CH4.

The annual emission (***Em***) of ***g*** type (***g***=1 CH4; ***g***=2 N2O) of non-CO2 GHG from emission source ***s (s***=1 enteric fermentation; ***s***=2 manure management; ***s***=3 rice cultivation; ***s***=4 agricultural soils*;* ***s***=5 agricultural residues) in year ***y*** are calculated by eq. (S1).

eq. (S1)

Where ***ACT*** is the activity level of the emission source; ***EF*** is the emission factor of the emission source in process ***p*** in region ***r***.

Detailed methods for each source are listed as follows.

**Enteric Fermentation**

Annual CH4 emissions of enteric fermentation () are calculated by eq.(S2).

eq. (S2)

Where is the emission factor for the defined livestock population (kg CH4 head-1 yr-1); is the number in stock of livestock category ***c*** (heads).

**Manure Management**

Annual CH4 emissions from manure management () are calculated by eq.(S3).

eq. (S3)

Where is the emission factor for the defined livestock population (kg CH4 head-1 yr-1); is the number in stock of livestock category ***c*** (heads).

Annual N2O emissions from manure management () are calculated by eq.(S4).

eq. (S4)

Where is the number of head of livestock category ***c*** (heads); is the annual average nitrogen (N) excretion per head of livestock category ***c*** (kg N head-1 yr-1); is the fraction of total N excretion for each livestock category ***c*** that is managed in manure management system ***MS*** (dimensionless); is the emission factor for direct N2O emissions from manure management system ***MS*** (kg N2O-N kg N-1); is the amount of manure nitrogen that is lost due to volatilization of ammonia or NOx (kg N yr-1); is the emission factor for N2O emission from atmospheric deposition of nitrogen on soil and water surface (kg N2O-N); is the amount of manure nitrogen that leached from manure management systems (kg N yr-1); is the emission factor for N2O emission from N leaching and runoff (kg N2O-N kgN-1); is the conversion of N2O-N emissions to N2O emissions.

**Rice cultivation**

Annual CH4 emissions from rice cultivation () are calculated by eq.(S5).

eq. (S5)

Where is the emission factors of rice in ecosystem ***sy*** (kg CH4 ha-1); is the annual sown area of rice in ecosystem ***sy*** (ha yr-1).

**Agricultural soils**

Annual N2O emissions from rice cultivation () are calculated by eq.(S6).

eq. (S6)

Where is the annual amount of synthetic N fertilizer applied to soils of upland system ***sy*** (kg N2O-N yr-1); is the annual amount of organic N fertilizer (including animal manure, compost, sewage sludge and other organic N additions) applied to soils of upland system ***sy*** (kg N2O-N yr-1); is the efficient factor for N2O emission from N input in upland system ***sy*** (kg kg-1); is the annual amount of synthetic N fertilizer applied to flooded rice (kg N2O-N yr-1); is the annual amount of organic N fertilizer applied to flooded rice (kg N2O-N yr-1); is the efficient factor for N2O emission for flooded rice (kg kg-1); is the annual amount of synthetic N fertilizer applied to soils (kg N2O-N yr-1); is the fraction of synthetic N fertilizer that volatilizes as NH3 or NOx (kg kg-1); is the annual amount of organic N additions to soils(kg N2O-N yr-1); is the annual amount of N deposited(kg N2O-N yr-1); is the fraction of organic N addition and deposited N that that volatilizes as NH3 or NOx (kg kg-1); is the emission factor for N2O emission from atmospheric deposition of N on soils and water surface(kg kg-1); is the conversion of N2O-N emissions to N2O emissions.

**Burning of agricultural residues**

Annual CH4 emissions from burning of agricultural residues () are calculated by eq.(S7).

eq. (S7)

Where is the annual dry matter yield for crop ***i*** (kg yr-1); is the fraction of crop ***i*** burnt (%); is the combustion factor (dimensionless); is the emission factor for CH4 due to burning of agricultural residues (kg kg-1).

Annual N2O emissions from burning of agricultural residues () are calculated by eq.(S8).

eq. (S8)

Where is the annual dry matter yield for crop ***i*** (kg yr-1); is the fraction of crop ***i*** burnt (%); is the combustion factor (dimensionless); is the emission factor for N2O due to burning of agricultural residues (kg kg-1).

## S2 Sources for historical activity data

The historic activity data sources include the open National Data (http://https--data--stats--gov--cn--e4192.proxy.www.stats.gov.cn/easyquery.htm?cn=C01) (NBS, 2021),

China compendium of Statistics 1949-2008 (NBS, 2008a), Chinese Rural Statistical Yearbooks from 1985 (the earliest available from public source) to 2019 (the latest available for this paper) (NBS, 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008b, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019).

## S3 Emission factors

The choice of emission factors (EFs) for estimation of non-CO2 GHG emissions in AGHG-INV follows the methodology recommended in IPCC 2006 guidelines as closely as available data allows. We adopted the regional EFs for rice cultivation, manure management and enteric fermentation from the People’s Republic of China National Greenhouse Gas Inventory 2005 (PRCNGGI 2005). We also compile regional specific EFs for other source sector from published literature in English and Chinese, and the mean, minimum and maximum of these reported values are listed in Table S1 to Table S6.

Table S1 CH4 Emission factors (EFs) of enteric fermentation

|  |  |  |  |
| --- | --- | --- | --- |
| Animal type | CH4 Emission factors (EFs)  Unit: kg CH4 head-1 yr-1 | | |
| Min | Max | Mean |
| Beef Cattle | 50.0 | 87.7 | 63.9 |
| Dairy Cattle | 44.0 | 155.5 | 95.0 |
| Goat | 4.6 | 9.4 | 6.2 |
| Sheep | 5.0 | 9.4 | 6.3 |
| Donkey/Mule | 10.0 | 10.0 | 10.0 |
| Camel | 46.0 | 58.0 | 50.0 |
| Horse | 18.0 | 18.0 | 18.0 |
| Pig | 1.0 | 1.0 | 1.0 |

Source: Khalil et al., 1993; IPCC, 1996; Yamaji et al., 2003; Zhou et al., 2007; IPCC, 2006; NDRC, 2011; Edouard et al., 2019

Table S2 CH4 Emission factors (EFs) of manure management

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Animal type | CH4 emission factors (EFs) Unit: kg CH4 head-1 yr-1 | | | | | | | | |
| Northern China | | | Northwestern China | | | Northeastern China | | |
| Min | Max | Mean | Min | Max | Mean | Min | Max | Mean |
| Beef Cattle | 0.5 | 2.8 | 1.4 | 0.5 | 1.9 | 1.2 | 0.5 | 1.8 | 1.0 |
| Dairy Cattle | 0.5 | 12.0 | 7.8 | 0.5 | 12.0 | 7.4 | 0.5 | 9.5 | 6.0 |
| Goat | 0.5 | 0.2 | 0.2 | 0.5 | 0.1 | 0.2 | 0.5 | 0.1 | 0.2 |
| Sheep | 0.1 | 0.5 | 0.18 | 0.1 | 0.5 | 0.2 | 0.1 | 0.5 | 0.2 |
| Pig | 0.5 | 3.1 | 1.8 | 0.5 | 2.5 | 1.5 | 0.5 | 2.0 | 1.2 |
| Poultry | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 |
| Horse | 0.5 | 1.4 | 1.1 | 0.5 | 1.4 | 1.1 | 0.5 | 1.2 | 1.0 |
| Camel | 0.5 | 1.6 | 1.2 | 0.5 | 1.6 | 1.2 | 0.5 | 1.3 | 1.2 |
| Donkey/Mule | 0.5 | 0.8 | 0.6 | 0.5 | 0.8 | 0.6 | 0.5 | 0.6 | 0.6 |
| Animal type | Eastern China | | | Central & Southern China | | | Southwestern China | | |
| Min | Max | Mean | Min | Max | Mean | Min | Max | Mean |
| Beef Cattle | 0.5 | 5.6 | 2.2 | 0.5 | 8.2 | 2.7 | 0.5 | 2.0 | 1.6 |
| Dairy Cattle | 0.5 | 16.4 | 10.6 | 0.5 | 21.3 | 11.8 | 0.5 | 21.3 | 11.3 |
| Goat | 0.5 | 0.13 | 0.2 | 0.5 | 0.1 | 0.2 | 0.5 | 0.1 | 0.3 |
| Sheep | 0.1 | 0.5 | 0.2 | 0.1 | 0.5 | 0.2 | 0.1 | 0.5 | 0.3 |
| Pig | 0.5 | 5.1 | 3.0 | 0.5 | 5.9 | 3.4 | 0.5 | 5.4 | 3.1 |
| Poultry | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Horse | 0.5 | 1.6 | 1.4 | 0.5 | 1.6 | 1.4 | 0.5 | 1.9 | 1.4 |
| Camel | 0.5 | 1.9 | 1.6 | 0.5 | 2.2 | 1.6 | 0.5 | 2.2 | 1.6 |
| Donkey/Mule | 0.5 | 0.9 | 0.8 | 0.5 | 1.1 | 0.8 | 0.5 | 1.1 | 0.8 |

Source: IPCC, 2006; Zhou et al., 2007; NDRC, 2011

Table S3 N2O Emission factors (EFs) of manure management

|  |  |  |  |
| --- | --- | --- | --- |
| Animal type | N2OEmission factors (EFs)  Unit: kg N2O head-1 yr-1 | | |
| Min | Max | Mean |
| Beef Cattle | 0.26 | 0.98 | 0.30 |
| Dairy Cattle | 0.74 | 1.68 | 0.80 |
| Goat | 0.03 | 0.09 | 0.05 |
| Sheep | 0.03 | 0.09 | 0.05 |
| Donkey/Mule | 0.11 | 0.19 | 0.15 |
| Camel | 0.17 | 0.33 | 0.20 |
| Horse | 0.20 | 0.33 | 0.25 |
| Pig | 0.08 | 0.20 | 0.10 |
| Poultry | 0.004 | 0.007 | 0.005 |

Source: IPCC, 2006; NDRC, 2011; Guo et al., 2017; Hu et al., 2019; Zhou et al., 2014

Table S4 N2O Emission factors (EFs) of different manure management systems

|  |  |  |  |
| --- | --- | --- | --- |
| Manure management system | N2OEmission factors (EFs)  Unit: kg N2O head-1 yr-1 | | |
| Min | Max | Mean |
| Pasture/Range/Paddock (cattle) | - | - | 0.02 |
| Pasture/Range/Paddock (goat and sheep) | - | - | 0.01 |
| Daily spread | - | - | 0 |
| Solid storage | - | - | 0.005 |
| Dry lot | - | - | 0.02 |
| Liquid storage | - | - | 0.005 |
| Compost | - | - | 0.01 |
| Matting | - | - | 0.01 |
| Aerobic treatment | - | - | 0.005 |
| Anaerobic digester | - | - | 0 |
| Other | - | - | 0.01 |

Source: NDRC, 2011; Zhou et al., 2014

Table S5 CH4 Emission factors (EFs) of rice cultivation

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| District | Rice type | CH4 Emission factors (EFs)  Unit: kg CH4 ha-1 | | | Source |
| Min | Max | Mean |
| AEZ5 | Single Rice | 24.19 | 785.57 | 268.92 | Chen et al., 1995; Li et al., 1997; Wang et al., 2000; Yao et al.,1994 |
| AEZ6A | Single Rice | 18.82 | 290.30 | 120.92 | Chen et al., 1993; Zou et al., 2005; Tao et al., 1993; Cai et al., 2000; Zhen et al.,1997 |
| AEZ6A | Early Rice | 18.82 | 591.36 | 157.60 | Lin et al.,2000 |
| AEZ6A | Late Rice | 18.82 | 591.36 | 157.60 | Lin et al.,2000 |
| AEZ6B | Single Rice | 419.33 | 806.40 | 593.15 | Khalil et al., 1998; Cao et al.,1996; Cai et al.,2000 |
| AEZ7 | Single Rice | 87.60 | 556.80 | 264.26 | Lu et al., 2000; Duan et al.,1999 |
| AEZ7 | Early Rice | 21.77 | 868.22 | 265.03 | Lu et al., 2000; Wassmann et al.,1993, 1996; Cai et al., 2000; Tao et al., 1998 |
| AEZ7 | Late Rice | 21.77 | 868.22 | 265.03 | Lu et al., 2000; Wassmann et al.,1993, 1996; Cai et al., 2000; Tao et al., 1998 |
| AEZ8 | Single Rice | 13.44 | 188.16 | 54.42 | Yue et al., 2005; Yan et al., 2000 |

Table S6 N2O Emission factors (EFs) of nitrogen addition from different crop fields

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Land use type | Crops | N2O Emission factors (EFs) of applied fertilizer (Unit: %) | | |
| Min | Max | Mean |
| Upland | Vegetables | 0.61 | 1.64 | 0.87 |
| Upland | Grain crops | 0.08 | 0.82 | 0.59 |
| Upland | Other upland crops | 0.25 | 1.10 | 0.68 |
| Paddy fields | Rice | 0.30 | 0.68 | 0.49 |
| Orchard |  | 0.75 | 0.75 | 0.75 |
| Tea garden |  | 1.2 | 1.9 | 1.6 |

Source: NDRC, 2011; Xu et al., 2016; Shi et al., 2010; Wang et al., 2008; Ju et al., 2017; Wang et al., 2018; Wang et al., 2019

## S4 Description of Business-as-usual Scenario

Business-as-usual (BAU) scenario continues the current trends in key drivers, including population, urbanization, economic development, agricultural development, and diets. Our basic premise is that future emissions is determined by future demand for agricultural production, which will likely be shaped by two primary factors, population and per capita food consumption.

**Population and urbanization**, we used data from *World Population Prospect 2019* and *World Urbanization Prospect 2018* by United Nations Department of Economic and Social Affairs (https://population.un.org/wpp/). Nine future population scenarios to 2100, including medium fertility variant, high fertility variant, low fertility variant, constant-fertility variant, instant-replacement-fertility variant, momentum variant, zero-migration variant, constant-mortality variant, and no change variant, and one urbanization rate scenario to 2050 are provided for China, and their ranges are illustrated by Figure S1(a) and (b). The urbanization rates from 2051 to 2060 are obtained by applying Vector Autogression model (VAR), which is commonly used for multivariate time series.

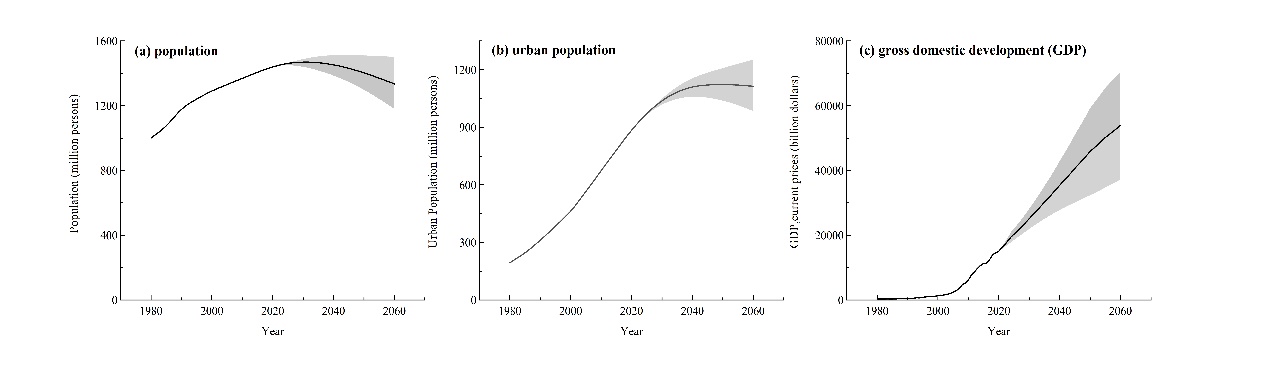


Figure S1 Projected trends of (a) population; (b) urban population; and (c) gross domestic product (GDP) in China to 2060

**Economic development**, we used the average projections by Organization for Economic Co-operation and Development (OECD) Economic Outlook (<https://stats.oecd.org/>), *The China in 2030* by the World Bank and China’s Development Research Center of the State Council (2013), and International Monetary Fund World Economic Outlook Database (<https://www.imf.org/en/Publications/WEO/weo-database/2021/April>). But all outlooks only project the gross domestic product (GDP) in China to 2030, so we apply VAR, based on historic GDP from 1980 to 2019 and projected GDP from 2020 to 2030, to predict the GDP to 2060, as shown in Figure S1(c).

**Diet change**, we adopt four models to produce high vs low projected estimates of future demand of six animal-based products (beef, pork, mutton, poultry meat, milk and egg), because there is no single universally-accepted method of forecasting temporal change of consumption patterns. But only the average estimate is used for projecting the future emissions. In the first method, we consider the relationship between per capita consumption and per capita GDP (Du et al., 2018). We compiled consumption data from 1980 to 2018 from national statistical database (<https://data.stats.gov.cn/easyquery.htm?cn=C01>). We also apply two regression models, i.e. ordinary least squares (OLS) and VAR, to predict changing consumption pattern to 2060, based on the empirical changes between population, per capita GDP, and consumption from 1980 to 2018. We also integrate data in OECD-FAO Agricultural Outlook (Edition 2020), which project the per capita consumption to 2029 (<https://data.oecd.org/agroutput/meat-consumption.htm>). As shown in Figure 2S, different levels of uncertainties exist for future demand of the six animal-source products. Diets are rooted in culture and traditions while responding to changing lifestyle driven by for instance by urbanization and changing income.

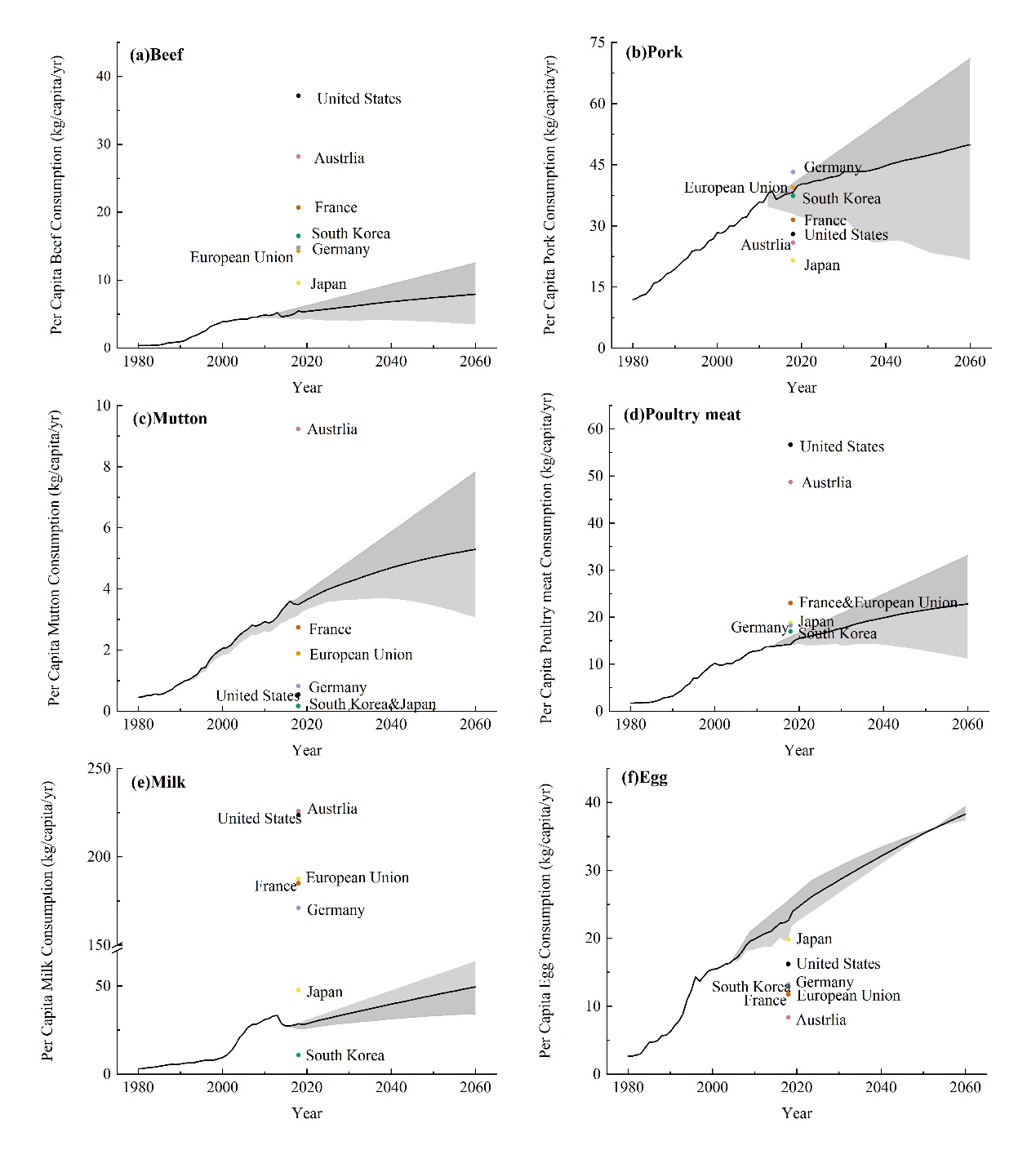


Figure S2 Projected trends of per capita consumption in China of (a)beef; (b) pork; (c) mutton; (d) poultry meat; (e)milk; and (f) egg

**Agricultural development**. We calculated a statistical extrapolation of historical trends to forecast future domestic crop production using provincial-scale data. We compiled data from the national statistical database and then forecast total production and sown areas for each crop for each province, using VAR. The national predictions of major crops were calibrated with the estimates for rice, wheat, maize, soybean, cotton, sugar crops, potato, fruit, and vegetables, to 2030 of Chinese Agriculture Outlook Report by China Agricultural Monitoring and Early-warning System (CAMES) (Committee for Market Warning, 2021). For livestock production, we forecast domestic production by extrapolating the historic relationship between livestock production and consumption into future. The predictions for pork, poultry meat, ruminants’ meat (beef and mutton), egg and milk at national level are also calibrated with the CAMES estimates (Committee for Market Warning, 2021). For those having very radical trends, if the prediction will increase or decrease more than by 40% compared with that in 2018, the production will be frozen since the year. The domestic production of major crops and livestock to 2060 are illustrated in Table S7 and S8.

Table S7 Production of major crops in the BAU scenario

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Crop | Total production (Mt) | | | | |
| 2018 | 2030 | 2040 | 2050 | 2060 |
| Rice | 212.1 | 222.5 | 223.1 | 223.1 | 223.1 |
| Wheat | 131.4 | 135.8 | 137.4 | 139.0 | 140.6 |
| Maize | 257.2 | 331.7 | 353.4 | 353.4 | 353.4 |
| Beans | 19.2 | 20.9 | 21.8 | 21.8 | 21.8 |
| Cotton | 6.1 | 5.5 | 5.5 | 5.5 | 5.5 |
| Sugar crops | 119.4 | 119.8 | 120.2 | 120.2 | 120.2 |
| Potato | 28.7 | 25.8 | 23.2 | 20.9 | 20.9 |
| Fruit | 256.9 | 294.0 | 309.1 | 346.8 | 366.8 |
| Vegetable and melon | 784.7 | 798.0 | 814.8 | 818.3 | 895.1 |

Table S8 Production of major livestock in the BAU scenario

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Crop | Total production (Mt) | | | | |
| 2018 | 2030 | 2040 | 2050 | 2060 |
| Pork | 54.0 | 60.0 | 61.6 | 61.4 | 58.7 |
| Beef | 6.4 | 7.9 | 8.7 | 9.4 | 9.4 |
| Mutton | 4.8 | 5.8 | 6.8 | 6.8 | 6.8 |
| Poultry meat | 23.6 | 25.6 | 27.7 | 30.0 | 32.5 |
| Egg | 31.3 | 36.5 | 40.2 | 44.2 | 44.2 |
| Milk | 30.4 | 43.9 | 45.0 | 45.6 | 45.6 |

## S5 Description of Technical potential and Maximum technical potential scenarios

We conducted meta-analysis to evaluate the reduction efficiency (RE) and technical applicability (TA) of the selected 17 technologies (Uprety et al., 2012; Gerber et al., 2013; Hristov et al., 2013). The implementation potential (IP) were assumed on the basis of public report and consultation with 10 experts in this field. The RE, TA and TP of each technology in crop farming sector and in livestock feeding sector are listed in Table S9 and Table S10.

## S6 Uncertainty analysis

**Activity data.** The sum of provincial data is not always the same with national data from National statistical system or international organization. The difference is shown in Table S11 and Table S12.

**Emission factors.** The ranges of key emission factors (EFs) are listed in the Table S1 to Table S6.

**Projected data of driving forces.** The ranges of estimates of key driving forces and their coefficients of variants (CVs) are listed in Table S13. From which we can see, great uncertainties exist in the projections of GDP and future consumptions of the 6 animal-sourced products, CVs of which are usually above 40%.

**Uncertainties between spatial scales** are listed in Table S14, due to the aggregation and disaggregation processes.

## S7 Supplement results

The non-CO2 GHG emissions under the three scenarios for each province are listed in Table S15.

Table S9 The reduction efficiency (RE), technical applicability (TA), and implementation potential (IP) for technologies in crop farming sector

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Technology | Greenhouse gas | Reduction efficiency (%) | Technical applicability | Implementation potential in 2060 | |
| TP | MTP |
| C1 | N2O | 30 | All crops | Vegetable and fruits | All crops |
| C2 | N2O | TP: 10; MTP: 20 | All crops | 100% in 2025 *a* | 100% in 2025 |
| C3 | N2O | 16 | All crops | 50% | 100% |
| C4 | N2O | 40 | All crops | 40% | 100% |
| CH4 | 43 |
| C5 | N2O | 42 | All crops | 40% *b* | 100% |
| CH4 | 52 |
| C6 | N2O | TP:10; MTP: 30 | Upland crops | 100% | 100% |
| C7 | N2O | 20 | All crops | 40% | 100% |
| C8 | N2O | 32 | Upland crops | 50% | 100% |
| C9 | CH4 | 50 | Rice paddy field | 30% | 100% |
| C10 | CH4 | 29 | Rice paddy field | 40% | 100% |
| C11 | CH4 | 28 | Rice paddy field | 40% | 100% |

*a* According to Zhang (2019), the implementation area of Formula Fertilization by Soil Testing amounted to 128 million ha (89.3% of total arable land in China) in 2019 (https://www.chinacourt.org/article/detail/2019/12/id/4734396.shtml).

*b* In 2019, the implementation area of all new types of fertilizer, including slow release fertilizer and water soluble fertilizer amounted to 16.3 million ha (11% of total arable land in China) (https://www.chinacourt.org/article/detail/2019/12/id/4734396.shtml).

Table S10 The reduction efficiency (RE), technical applicability (TA), and implementation potential (IP) for technologies in livestock feeding sector

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Technology | Greenhouse gas | Reduction efficiency (%) | Technical applicability | Implementation potential in 2060 | |
| TP | MTP |
| L1 | CH4 | 30 | All ruminants | 50% | 100% |
| L2 | CH4 | TP: 20; MTP: 40 | All ruminants | 100% | 100% |
| N2O | TP: 20; MTP: 40 |
| L3 | CH4 | TP: 10; MTP: 20 | All ruminants | 20% | 40% |
| L4 *a* | CH4 | TP: 20; MTP: 40 | All animals | 100% | 100% |
| N2O | TP: 20; MTP: 40 |
| L5 *a* | CH4 | 20 | All animals | 30% | 40% |
| N2O | 40 |
| L6 *a* | CH4 | 60 | All animals | 20% | 30% |

*a* The implementation rate of L4, L5, and L6 are from the People’s Republic of China National Greenhouse Gas Inventory 2005 (PRCNGGI 2005) and Zhu et al. (2020).

Table S11 Differences of activity data among provincial-level, national and international statistics in 2010

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Item | Description | Unit | Provincial | National | International *a* | CV (%) |
| Synthetic fertilizer | Application | Million tonne (Mt) | 55.6 | 55.6 | 51.1 | 4.8% |
| Rice | Production | Million tonne (Mt) | 197.2 | 197.2 | 195.8 | 0.4% |
| Wheat | Production | Million tonne (Mt) | 116.1 | 116.1 | 115.2 | 0.4% |
| Maize | Production | Million tonne (Mt) | 190.8 | 190.8 | 177.4 | 4.2% |
| Soybeans | Production | Million tonne (Mt) | 15.4 | 15.4 | 15.1 | 1.1% |
| Potatoes | Production | Million tonne (Mt) | 15.3 | 15.3 | 76.5 | 99.0% |
| Cotton | Production | Million tonne (Mt) | 5.8 | 5.8 |  | 0.0% |
| Rapeseed | Production | Million tonne (Mt) | 12.8 | 12.8 | 13.1 | 1.3% |
| Sugar crops | Production | Million tonne (Mt) | 113.0 | 113.0 | 120.1 | 3.6% |
| Vegetable | Production | Million tonne (Mt) | 572.6 | 572.6 | 457.4 | 12.5% |
| Fruit | Production | Million tonne (Mt) | 201.0 | 201.0 | 195.1 | 1.7% |
| Beef cattle | Number in stock | Million heads | 67.4 | 84.0 | -*a* | 6.5% |
| Dairy cattle | Number in stock | Million heads | 16.4 | 14.2 | - *a* | 10.2% |
| Sheep | Number in stock | Million heads | 138.9 | 145.4 | 145.3 | 2.6% |
| Goat | Number in stock | Million heads | 142.0 | 142.0 | 142.0 | 0.0% |
| Horses | Number in stock | Million heads | 6.8 | 5.3 | 5.3 | 14.9% |
| Asses | Number in stock | Million heads | 6.4 | 5.1 | 5.1 | 13.6% |
| Mules | Number in stock | Million heads | 2.7 | 1.9 | 1.9 | 21.3% |
| Pigs | Number in stock | Million heads | 464.6 | 467.7 | 467.7 | 0.4% |
| Poultry | Number in stock | Billion heads | 5.4 | 5.4 | 6.3 | 9.1% |
| Urban population |  | Million capita | 671.4 | 669.8 | 669.4 | 0.2% |
| Rural population |  | Million capita | 671.13 | 671.13 | 690.4 | 1.6% |

*a* Data source: FAOSTAT (http://www.fao.org/faostat/en/)

*b* In FAOSTAT, there is no data for beef cattle and dairy cattle, but data on buffaloes (29.5 million heads) and cattle (68.7 million heads)

Table S12 Differences of activity data among provincial-level, national and international statistics in 2018

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Item | Description | Unit | Provincial | National | International *a* | CV (%) |
| Synthetic fertilizer | Application | Million tonne (Mt) | 56.5 | 56.5 | 45.6 | 11.9% |
| Rice | Production | Million tonne (Mt) | 212.1 | 212.1 | 212.1 | 0.0% |
| Wheat | Production | Million tonne (Mt) | 131.4 | 131.4 | 131.4 | 0.0% |
| Maize | Production | Million tonne (Mt) | 257.2 | 257.2 | 257.2 | 0.0% |
| Soybeans | Production | Million tonne (Mt) | 16.0 | 16.0 | 16.0 | 0.0% |
| Potatoes | Production | Million tonne (Mt) | 18.0 | 18.0 | 90.3 | 99.2% |
| Cotton | Production | Million tonne (Mt) | 6.1 | 6.1 | 18.5 | 70.0% |
| Rapeseed | Production | Million tonne (Mt) | 13.3 | 13.2 | 13.3 | 0.4% |
| Sugar crops | Production | Million tonne (Mt) | 119.4 | 119.4 | 119.4 | 0.0% |
| Vegetable | Production | Million tonne (Mt) | 703.4 | 703.4 | 573.8 | 11.3% |
| Fruit | Production | Million tonne (Mt) | 256.9 | 256.9 | 239.1 | 4.1% |
| Beef cattle | Number in stock | Million heads | 66.2 | 66.2 | -*b* | 12.3% |
| Dairy cattle | Number in stock | Million heads | 10.4 | 10.4 | -*b* | 0.0% |
| Sheep | Number in stock | Million heads | 161.4 | 161.4 | 161.4 | 0.0% |
| Goat | Number in stock | Million heads | 135.7 | 135.7 | 135.7 | 0.0% |
| Horses | Number in stock | Million heads | 3.5 | 34.7 | 34.7 | 129.7% |
| Asses | Number in stock | Million heads | 2.5 | 25.3 | 25.3 | 130.1% |
| Mules | Number in stock | Million heads | 0.8 | 0.8 | 0.8 | 0.0% |
| Pigs | Number in stock | Million heads | 428.2 | 428.2 | 428.2 | 0.0% |
| Poultry | Number in stock | Billion heads | 6.0 | 6.0 | 6.1 | 1.0% |
| Urban population |  | Million capita | 839.4 | 864.33 | 837.0 | 1.8% |
| Rural population |  | Million capita | 557.07 | 541.08 | 578.0 | 3.3% |

*a* Data source: FAOSTAT (http://www.fao.org/faostat/en/)

*b* In FAOSTAT, there is no data for beef cattle and dairy cattle, but data on buffaloes (27.1 million heads) and cattle (63.3 million heads)

Table S13 Comparisons and coefficients of variations (CVs) of projected driving forces from different sources or models

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Item | Description | Unit | Estimates in 2060 | | | CV (%) |
| Min | Max | Mean |
| Population | - | Million capita | 1.17 | 1.51 | 1.33 | 8.7 |
| Urban population | - | Million capita | 0.98 | 1.26 | 1.11 | 17.5 |
| GDP | - | trillion dollars, current price | 37.0 | 70.9 | 54.0 | 44.4 |
| Beef | Per capita consumption | kg capita-1 | 3.4 | 12.5 | 7.9 | 57.3 |
| Pork | Per capita consumption | kg capita-1 | 21.5 | 58.9 | 49.9 | 42.3 |
| Mutton | Per capita consumption | kg capita-1 | 3.1 | 7.8 | 5.3 | 45.3 |
| Poultry meat | Per capita consumption | kg capita-1 | 11.1 | 33.1 | 22.8 | 48.6 |
| Milk | Per capita consumption | kg capita-1 | 34.4 | 64.5 | 49.4 | 43.0 |
| Egg | Per capita consumption | kg capita-1 | 37.2 | 39.4 | 38.3 | 4.0 |

Table S14 Uncertainties between estimates at different spatial scales (%)

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Unit: % | 2018 | 2030 | | | 2040 | | | 2050 | | | 2060 | | |
| BAU | TP | MTP | BAU | TP | MTP | BAU | TP | MTP | BAU | TP | MTP |
| Difference between estimates at national and provincial level *a* | 8.6 | 16.7 | 20.4 | 32.5 | 17.1 | 19.3 | 39.6 | 13.0 | 21.7 | 51.7 | 10.9 | 36.2 | 54.3 |

Table S15 Non-CO2 GHG emissions for each province under three scenarios (Unit: Mt CO2-eq)

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Province  Unit: Mt CO2-eq | 2018 | 2030 | | | 2040 | | | 2050 | | | 2060 | | |
| BAU | TP | MTP | BAU | TP | MTP | BAU | TP | MTP | BAU | TP | MTP |
| Beijing | 0.68 | 0.79 | 0.71 | 0.60 | 0.88 | 0.75 | 0.55 | 0.95 | 0.77 | 0.53 | 0.99 | 0.72 | 0.53 |
| Tianjin | 2.01 | 2.30 | 2.00 | 1.65 | 2.49 | 2.06 | 1.49 | 2.62 | 2.07 | 1.41 | 2.71 | 1.93 | 1.41 |
| Hebei | 25.19 | 29.18 | 25.46 | 20.98 | 31.73 | 26.33 | 18.76 | 33.40 | 26.39 | 17.59 | 34.44 | 24.24 | 17.40 |
| Shanxi | 9.48 | 11.31 | 10.00 | 8.41 | 12.34 | 10.44 | 7.61 | 12.98 | 10.52 | 7.17 | 13.34 | 9.72 | 7.11 |
| Inner Mongolia | 42.01 | 54.10 | 48.31 | 41.25 | 60.08 | 51.70 | 37.18 | 63.40 | 52.33 | 34.30 | 65.05 | 47.74 | 33.90 |
| Liaoning | 20.74 | 24.28 | 20.60 | 16.16 | 26.03 | 20.90 | 13.95 | 27.07 | 20.61 | 12.93 | 27.66 | 18.53 | 12.82 |
| Jilin | 20.64 | 22.53 | 19.29 | 15.18 | 24.31 | 19.70 | 13.40 | 25.36 | 19.52 | 12.63 | 26.00 | 17.73 | 12.61 |
| Heilongjiang | 32.37 | 36.29 | 31.14 | 24.81 | 39.25 | 31.98 | 22.08 | 41.16 | 31.99 | 20.97 | 42.39 | 29.41 | 21.03 |
| Shanghai | 1.52 | 1.62 | 1.38 | 1.10 | 1.69 | 1.36 | 0.97 | 1.75 | 1.34 | 0.94 | 1.79 | 1.23 | 0.93 |
| Jiangsu | 26.71 | 27.47 | 21.76 | 14.72 | 28.02 | 20.16 | 11.42 | 28.41 | 18.82 | 10.43 | 28.61 | 16.15 | 10.10 |
| Zhejiang | 9.51 | 9.65 | 7.55 | 5.02 | 9.77 | 6.92 | 3.74 | 9.85 | 6.40 | 3.33 | 9.87 | 5.40 | 3.18 |
| Anhui | 29.06 | 30.15 | 23.95 | 16.41 | 30.93 | 22.48 | 12.85 | 31.45 | 21.18 | 11.77 | 31.73 | 18.32 | 11.49 |
| Fujian | 12.21 | 12.57 | 9.99 | 6.79 | 12.76 | 9.22 | 5.20 | 12.89 | 8.55 | 4.67 | 12.93 | 7.25 | 4.47 |
| Jiangxi | 34.73 | 36.67 | 28.63 | 19.29 | 37.72 | 27.09 | 14.51 | 38.35 | 25.60 | 12.91 | 38.67 | 21.93 | 12.61 |
| Shandong | 33.80 | 37.89 | 33.22 | 27.65 | 40.86 | 34.10 | 24.86 | 42.77 | 34.06 | 23.41 | 43.92 | 31.39 | 23.12 |
| Henan | 41.72 | 45.10 | 38.95 | 31.55 | 47.78 | 38.97 | 27.69 | 49.46 | 38.26 | 25.88 | 50.39 | 34.81 | 25.31 |
| Hubei | 34.69 | 35.92 | 29.44 | 21.72 | 37.28 | 28.31 | 17.75 | 38.10 | 27.00 | 16.19 | 38.50 | 23.64 | 15.66 |
| Hunan | 54.01 | 56.93 | 45.84 | 33.06 | 58.89 | 43.90 | 26.27 | 60.09 | 41.79 | 23.69 | 60.69 | 36.35 | 22.98 |
| Guangdong | 30.93 | 32.74 | 26.20 | 18.26 | 33.32 | 24.35 | 14.23 | 33.71 | 22.71 | 12.85 | 33.85 | 19.45 | 12.33 |
| Guangxi | 38.07 | 41.10 | 34.04 | 25.50 | 42.78 | 33.02 | 21.21 | 43.77 | 31.69 | 19.49 | 44.26 | 27.96 | 18.98 |
| Hainan | 6.53 | 6.85 | 5.68 | 4.27 | 7.14 | 5.50 | 3.56 | 7.31 | 5.25 | 3.26 | 7.39 | 4.61 | 3.15 |
| Chongqing | 20.85 | 21.62 | 16.99 | 11.51 | 22.22 | 16.04 | 8.74 | 22.58 | 15.13 | 7.81 | 22.75 | 12.97 | 7.61 |
| Sichuan | 77.41 | 84.84 | 69.74 | 52.17 | 89.50 | 69.03 | 42.93 | 92.32 | 67.12 | 39.11 | 93.91 | 59.35 | 38.50 |
| Guizhou | 31.77 | 33.87 | 28.00 | 21.10 | 35.87 | 27.89 | 17.36 | 37.00 | 27.14 | 15.68 | 37.58 | 23.93 | 15.36 |
| Yunnan | 53.62 | 58.66 | 49.69 | 39.07 | 62.68 | 50.24 | 33.31 | 64.96 | 49.34 | 30.47 | 66.16 | 44.08 | 29.93 |
| Tibet | 19.36 | 23.06 | 20.93 | 18.32 | 26.02 | 22.93 | 16.75 | 27.68 | 23.49 | 15.46 | 28.57 | 21.58 | 15.42 |
| Shaanxi | 12.82 | 14.36 | 12.31 | 9.84 | 15.49 | 12.51 | 8.54 | 16.15 | 12.31 | 7.85 | 16.51 | 11.03 | 7.67 |
| Gansu | 20.34 | 24.98 | 22.35 | 19.16 | 27.73 | 23.95 | 17.25 | 29.22 | 24.24 | 15.88 | 29.97 | 22.10 | 15.72 |
| Qinghai | 17.48 | 20.33 | 18.38 | 16.02 | 22.87 | 20.05 | 14.53 | 24.23 | 20.45 | 13.32 | 24.92 | 18.67 | 13.23 |
| Ningxia | 6.11 | 7.35 | 6.52 | 5.51 | 8.23 | 7.03 | 5.01 | 8.79 | 7.19 | 4.69 | 9.12 | 6.63 | 4.71 |
| Xinjiang | 30.65 | 39.20 | 34.76 | 29.32 | 43.60 | 37.20 | 26.33 | 46.20 | 37.76 | 24.35 | 47.60 | 34.44 | 24.22 |

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