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Sectoral changing patterns of China's green GDP considering climate change: An investigation based on the economic input-output life cycle assessment model

Shu Wu [a, b, c], Hongyun Han [a, *]

[a] Center for Agricultural and Rural Development, School of Public Affairs, Zhejiang University, Hangzhou 310058, China
[b] School of Management, Zhejiang University, Hangzhou 310058, China
[c] School for Environment and Sustainability, University of Michigan, Ann Arbor 48105, USA

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ABSTRACT

The rapid growth of energy-intensive and high-emission industries has underpinned China's economic boom over the past few decades. Since her economic development entered the new normal phase in 2013, China has faced the challenge of mitigating greenhouse gas (GHG) emissions while achieving medium-high economic growth. Transforming the economic development pattern and restructuring the economy is a principal solution, and one important prerequisite is discerning great sectoral disparities of GHG emissions and corresponding environmental costs because the diversity of characteristics among different sectors causes the pollutants that are discharged to vary. Hence, this paper aims to assess the environmental costs of China's total and sectoral GHG emissions. Based on the System of Environmental and Economic Accounts and using the economic input-output life cycle assessment model, this study calculates the green GDP and green output value of 27 sectors to reflect the environmental costs of GHG emissions in China during 1991–2016. The findings are as follows: (1) while China's direct GHG emissions increased from 3,040.60 million tons of carbon dioxide equivalent ($MtCO_2eq$) to 10,641.10 $MtCO_2eq$ during 1991–2014, declining trends were observed in the total and 16 sectors' direct GHG emissions in the subsequent two years; (2) although the ratios of direct GHG emissions to total GHG emissions in most sectors decreased, total GHG emissions in eight sectors rose first and then fell, and in 15 sectors continued to rise; (3) China's green GDP grew from 2,003.88 billion Chinese Yuan to 26,245.25 billion Chinese Yuan during 1991–2016, and the difference between China's GDP and green GDP decreased from 2.73% to 1.02%; and (4) differences between the output value and green output value decreased in over 20 sectors. Finally, some policy implications are given from the perspective of some key sectors of the Manufacturing industry, Agricultural sector, and Transport, storage, and post sector.

1. Introduction

GDP has long been criticized for its failure to measure real economic welfare, as it considers neither the cost of environmental degradation, natural resource depletion, and income inequities (Costanza et al., 2014), nor the value of goods and services that are not traded in the market (Talberth and Bohara, 2006). Since the 1960s, global environmental pollution and ecological degradation have emerged as constraints of sustainable development of both society and economy (Bartlmus and Seifert, 2018). Indeed, there is mounting concern over the accounting of the ecosystem (Garcia and You, 2017), aiming at establishing green accounting systems and exploring the interconnectedness between environment and economy (Maler et al., 2008). Many studies have been devoted to green GDP accounting worldwide, such as China' regional green GDP by deducting the costs of adverse environmental externalities from GDP (Yang and Poon, 2009), Wuyishan's green GDP by

Abbreviations: AFOLU, Agriculture, Forestry and Other Land Use; EIO-LCA, economic input-output life cycle assessment; IO, input-output; IPPU, Industrial Processes and Product Use; MEE, Ministry of Ecology and Environment of China; NBS, National Bureau of Statistics of China; SEEA, System of Environmental and Economic Accounts; CH_4, methane; CO_2, carbon dioxide; GHG, greenhouse gas; N_2O, nitrous oxide; CNY, Chinese Yuan; $MtCO_2eq$, million tons of carbon dioxide equivalent.

* Corresponding author.
E-mail addresses: wushu@zju.edu.cn (S. Wu), hongyunhan@zju.edu.cn (H. Han).

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incorporating the value of direct ecosystem services into GDP (Xu et al., 2010), Malaysia's green GDP adjusting for natural resource depletion and environmental damage (Vaghefi et al., 2015), Thailand's green GDP by depreciating the cost of greenhouse gas (GHG) emissions from GDP (Kunanuntakij et al., 2017), and Chilean green GPD corrected for resource depreciation and environmental destruction (Mardones and Rio, 2019). Moreover, the rapid growth of the global economy has been accompanied by tremendous changes in industrial structure (Bacchetta and Jansen, 2012), which strongly influence pollutant emissions (Xie et al., 2017). The assessment of the green output value of different sectors has also gained widespread attention, as evaluating the environmental costs of each sector constitutes the premise of effective emission reduction policy-making (Wang et al., 2018).

China has achieved remarkable economic growth due to the implementation of the reform and opening-up policy in 1978. During 1978–2017, China's real GDP increased from 367.87 billion Chinese Yuan (CNY) to 14,092.17 billion CNY, with an average growth rate of 9.54% per year (NBS, 2019a). However, this economic expansion has come at a high cost in terms of environmental issues (Liu and Raven, 2010), and climate change triggered by extensive GHG emissions is currently the most pressing one. Until 1978, China contributed only approximately 8.31% of global carbon dioxide (CO_2) emissions, which is much less than the United States (30.76%) or the European Union (25.11%). The rapid industrialization and economic growth that has occurred since then has changed this situation dramatically. In 2014, China emitted approximately 10.29 Gt CO_2 and contributed to 28.48% of global CO_2 emissions, which is nearly double the emissions of the United States (14.54%) and almost triple that of the European Union (8.97%) (World Bank, 2019). To address the issue of climate change in a meaningful way, the Chinese government announced a reduction target of 40.00–45.00% below 2005 levels by 2020 (Chinanews, 2015) and reaching the peaking of CO_2 emissions before 2030 (den Elzen et al., 2016). The above facts and targets highlight the necessity of redefining China's development to account for environmental costs of GHG emissions. Despite ongoing debates concerning the conceptualization and practices of green accounting, the Chinese government launched an official experiment in 2004 and released the first-ever report on environmental costs in 2006 (Zhang, 2007). Nevertheless, such attempt came to a premature end one year later due to insufficient and fragmented environmental bureaucracies, underestimating the degree of data collection, and lacking consistent environment valuation rules (Jason and Ying, 2010). After this, no official project on China's green GDP accounting has appeared.

Contrary to the short-lived official project, there is extensive literature relating to green GDP accounting in China. Some studies are theoretical discussions of the practices and development of green accounting in China, such as the reasons for the cancellation of China's green GDP accounting scheme (Qiu, 2007), the politics of the Chinese green GDP project (Steinhardt and Jiang, 2007), challenges for China's green GDP accounting (Li and Lang, 2010), and possible revival of the project (Wang, 2016); however, more focus has been given to green GDP accounting. Of the latter, the green gross output value at the province level or the city level, including 31 regions (Lu and Lo, 2007), Fujian province (Zhang et al., 2010), Tianjin city (Wang et al., 2011), Shangluo city (Guo et al., 2015), and Yulin city (Dou et al., 2016) and the green output value of particular economic sectors, including forestry (Ying et al., 2011), agriculture (Li et al., 2016), and the coal industry (Wang and Sheng, 2018) constitute the foci of attention. Few investigations have attempted to estimate the green output value of all sectors. However, China's industrialization process has led to rapid growth in total GHG emissions (Liu et al., 2012). It is vital to estimate China's sectoral green output value because the diversity of characteristics among different sectors causes the pollutants that are discharged to vary (Wu et al., 2019a), and a proper arrangement of industrial structure is conducive to mitigate pollutant emissions (Cole et al., 2005).

How much GHG, both direct and total, is emitted by different economic sectors in China? What is the difference between China's GDP/sectoral output value and green GDP/green sectoral output value? Unfortunately, the extant literature is insufficient to answer these questions. Based on the System of Environmental and Economic Accounts (SEEA), this study aims to use the economic input-output life cycle assessment (EIO-LCA) model to assess the green GDP and green output value of 27 sectors to reflect the environmental costs of GHG emissions in China during 1991–2016. This paper contributes to the existing literature in two ways. Firstly, while some studies measure only direct GHG emissions and treat them as total GHG emissions in China, the EIO-LCA model makes it possible to distinguish between direct and indirect emissions, and estimate total emissions. Secondly, to the best of the authors' knowledge, this is the first time that both the green GDP and green output value of 27 sectors reflecting the impact of GHG emissions in China are assessed. The subdivision of 27 sectors assists to reveal the push or pull forces of each sector to the total economy when taking the environmental cost of GHG emissions into consideration, and shed light on China's economic structural adjustment and the revival of its green GDP accounting.

The remainder of this paper proceeds as follows. Section 2 depicts the overall framework of green GDP accounting, the EIO-LCA model, and data used in this study. Section 3 presents the estimation results. Sections 4 provides discussion and policy implications. Section 5 ends the study with conclusions.

2. Methods and data

2.1. Methods

2.1.1. Overall framework

There are two mainstream definitions of green GDP (Li and Fang, 2014). The first definition denotes green GDP as the sum of the traditional GDP and the value of ecosystem services (Ochuodho and Alavalapati, 2016). The second defines green GDP as the traditional GDP minus the cost of environmental degradation and natural resource depletion (Kunanuntakij et al., 2017). Compared to the second definition, the first is in its infancy because the accounting of ecosystem services is still in the progress of conceptualization (Remme et al., 2015). In addition, to incorporate regional benefits of ecosystem services into national accounts (Bartelmus, 2009) or price goods and services from the ecosystem is problematic since most of them are not traded and priced by markets (Boyd, 2007).

In this study, green GDP/sectoral green output value is defined as the modification of the traditional GDP/sectoral output value to account for the environmental costs. The environmental cost in the study only refers to the environmental degradation cost incurred by GHG emissions for two reasons. First, no consensus exists on the weighting of different kinds of pollution and thereby, aggregating their economic costs still relies on subjective weighting (Egilmez et al., 2013). Second, limitations of data availability make it impossible to assess different kinds of environmental pollution among various sectors in China, such as water pollution and waste pollution. Specifically, environmental degradation cost of GHG emissions is the expenditure relating to the deterioration in environmental quality incurred by climate change, such as rising global temperature, extreme weather, desertification, shortages of food and water, extinction of species, and spread of disease and food poisoning. The assessment of China's green GDP and the green output value of 27 sectors is based on Eq. (1):

$$\text{Green GDP / Green output value} = \text{Traditional GDP/Sectoral output value} - \text{Environmental Cost} = \text{Traditional GDP/Sectoral output value} - \text{Cost of GHG Emissions} \quad (1)$$

Fig. 1 shows the overall methodology framework. First, since there are only six benchmark input-output (IO) tables and six extended IO tables, this study utilizes the matrix transformation technique method to update China's IO tables during 1991–2016. Second, China's 27 sectors' and residential sector's direct GHG emissions are calculated based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 Guidelines), which come from the Energy sector, the Industrial Processes and Product Use (IPPU) sector, and the Agriculture, Forestry and Other Land Use (AFOLU) sector. Third, the inverse Leontief matrix is calculated using the updated IO tables for the years between 1991 and 2016, and 27 sectors' total GHG emissions are estimated based on the EIO-LCA model. Finally, China's green GDP and the green output value of 27 sectors are calculated through the monetary valuation of GHG emissions.

2.1.2. EIO-LCA model

Numerous tools are available for assessing environmental impacts. Some commonly-used ones are Material Flow Analysis, Input-Output Analysis, Life-Cycle Assessment, System of Economic and Environmental Accounting, and Environmental Impact Assessment (Finnveden and Moberg, 2005). This study uses the EIO-LCA model to assess the environmental impacts of different sectors based on all economic exchange activities. Compared with other methods, the EIO-LCA model better suits the objectives of this study because it assesses the environmental impacts throughout a product's life, from raw materials through utilization to disposal (Finnveden and Moberg, 2005), and considers both direct and indirect impacts (Leontief, 1970). Moreover, the EIO-LCA model has been confirmed to possess the advantages of having more complete boundaries (Islam et al., 2016) and obviating truncation bias (Majeau-Bettez et al., 2011). In general, the EIO-LCA model extends the environmental data with IO tables to generate an overall system boundary (Egilmez et al., 2013).

Table 1 is a simplified version of the IO table. The intermediate demand column shows the input demand required by sector j from sector i. The final demand column is the aggregate final demand of household consumption, governmental consumption, fixed asset formation, changes in inventories, and net exports. The gross output column is the totaling of the intermediate demand and final demand. The intermediate input line reflects the input provided by sector i to sector j. The line of value added is the aggregation of compensation of employees, net taxes on production, depreciation of fixed assets, and operating surplus, whose sum is the traditional GDP. The total input line is the sum of intermediate input and value added. In Table 1, z_{ij} is the flow of input from sector i to sector j, F_i is the final demand for sector i's output, and X_i is the gross output of sector i. According to the characteristics of the IO table, there is a constraint for the elements, which is denoted as follows:

$$\sum_{j=1}^{n} z_{ij} + F_i = X_i \quad (2)$$

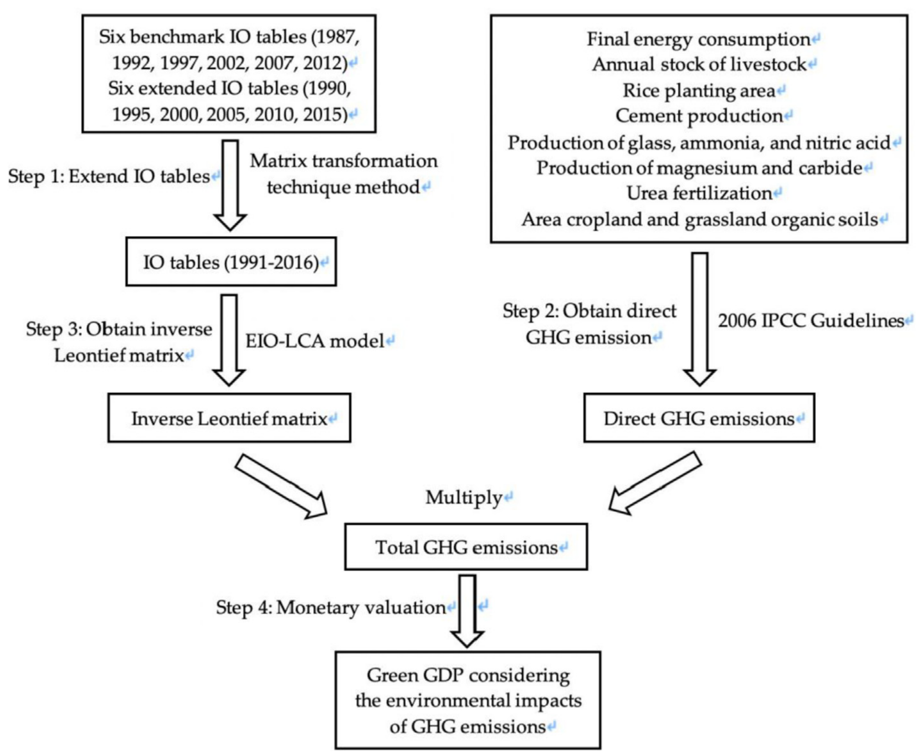

Fig. 1. Overall methodology framework of this study.

Table 1
A simplified version of the IO table.

Input		Output					
		Intermediate demand				Final demand	Gross output
		Sector j, j=1, 2, …, n					
Intermediate input	Sector i, i=1, 2, …, n	z_{11}	z_{12}	…	z_{1n}	F_1	X_1
		z_{21}	z_{22}	…	z_{2n}	F_2	X_2
		⋮	⋮		⋮	⋮	⋮
		z_{n1}	z_{n2}	…	z_{nn}	F_n	X_n
Value added		V_1	V_j	…	V_n	GDP	
Total input		X_1	X_j	…	X_n		

Eq. (2) implies that sector i consumes some of its annual output itself, supplies some to other sectors, and provides the rest to satisfy the final demands of household consumption, governmental consumption, fixed asset formation, changes in inventories, and net exports. By defining a technical coefficient $a_{ij} = z_{ij}/ X_j$, Eq. (2) can be rewritten as follows:

$$\sum_{j=1}^{n} a_{ij}X_j + F_i = X_i \tag{3}$$

After rearranged in a matrix form, the above equation is equivalent to:

$$X = \left[(I - A)^{-1}\right]F \tag{4}$$

where I is the n ∗ n identity matrix, A is the technical coefficient matrix, and $(I - A)^{-1}$ is the inverse Leontief matrix, which was first introduced by Leontief to estimate both direct and indirect transactions (Leontief, 1970). To assess the total environmental impacts, the economic output of each sector is multiplied by the multiplier matrix (Egilmez et al., 2013). A vector of total environmental impacts is shown as follows:

$$E = E_{dir}X = E_{dir}\left[(I - A)^{-1}\right]F \tag{5}$$

where E is the total environmental impacts, and E_{dir} is a diagonal matrix and represents direct environmental impacts. In this study, E_{dir} denotes a direct GHG emissions matrix of 27 sectors, and its diagonal element represents direct GHG emissions to produce one economic unit of output by each sector.

2.1.3. Direct GHG emissions

The 2006 Guidelines is an internationally accepted tool used to estimate GHG emissions (IPCC, 2006). The following types of GHG are covered, including CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, nitrogen trifluoride, trifluoromethyl sulfur pentafluoride, halogenated ethers, and other halocarbons. According to the 2006 Guidelines, Energy, IPPU, AFOLU, Waste, and Other are the five primary sources of GHG emissions. Due to limitations of data availability, this study estimates only the estimations of CO_2, CH_4, and N_2O from sources of Energy, IPPU, and AFOLU, which comprise the majority of GHG emissions in China. Fig. 2 shows the system boundary of GHG emissions in this study.

2.1.3.1. *Energy.* The Energy sector is the largest emitter of GHG, which typically contributes to over two-thirds of global GHG

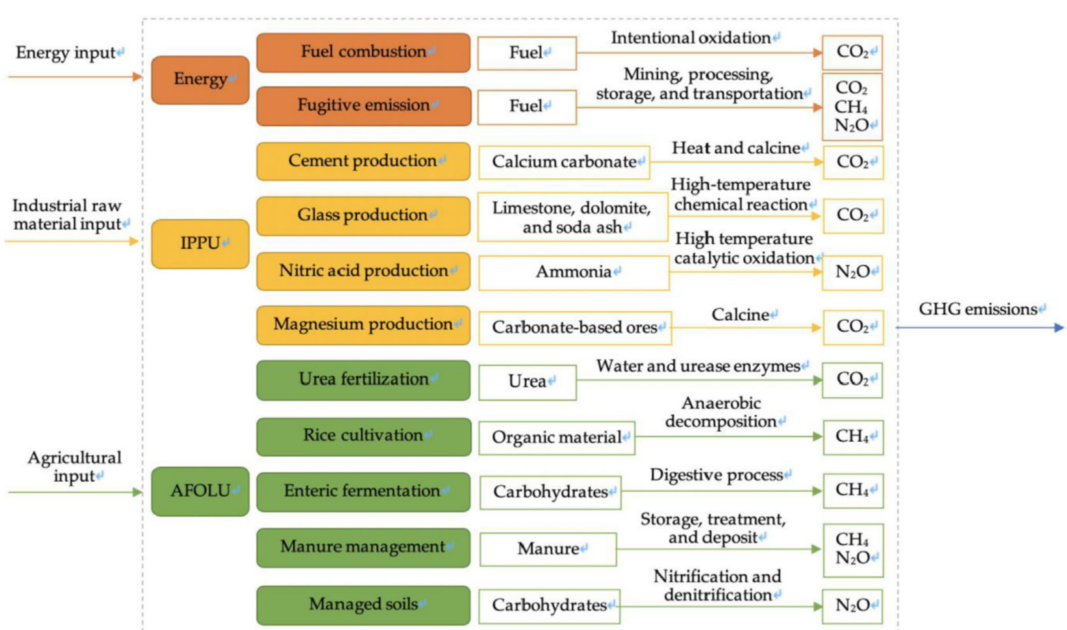

Fig. 2. System boundary of GHG emissions in this study.
Note: Other materials are not listed because the central focus is GHG.

emissions and at least 90.00% of the world's CO_2 emissions (IPCC, 2006). Combustion emissions and fugitive emissions are two major sources of energy-related GHG emissions. Combustion emissions are related to stationary combustion emissions from sources, such as power plants and refineries, and mobile combustion emissions from sources, such as road and other traffic. The ratio of the former to the latter is approximately 3:1. According to the classification of the China Energy Statistics Yearbook, there are 28 kinds of commonly used energy sources in China, including raw coal, cleaned coal, other washed coal, coke, coke oven gas, blast furnace gas, converter gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, naphtha, lubricants, paraffin waxes, white spirit, bitumen asphalt, petroleum coke, liquefied petroleum gas, refinery gas, other petroleum products, natural gas, liquefied natural gas, heat, electricity, and other energy. Besides, GHG may be emitted intentionally or unintentionally during the extraction, processing, and transport of fossil fuels, which is known as fugitive emissions. The sources of fugitive GHG emissions comprise underground coal mines, surface coal mining, abandoned underground coal mines, and oil and natural gas systems. Considering that the data of different types of coal mines are unavailable and underground coal mines are the dominant form of coal mines in China (Chen, 2010), it is assumed that all coal mines in China are underground coal mines. Eq. (A. 1) and Eq. (A. 2) in Appendix A show the calculation process.

2.1.3.2. IPPU. Industrial activities produce GHG through processes that chemically or physically transform materials, which accounts for the majority of China's total emissions (Wu et al., 2019b). Specifically, these sources include the mineral industry, the chemical industry, the metal industry, non-energy products from fuels and solvent use, the electronics industry, emissions of fluorinated substitutes for ozone-depleting substances, and other product manufacture and use. This paper only estimates four sources of GHG emissions from the IPPU sector due to data unavailability, including cement manufacture, glass production, nitric acid production, and magnesium production. Another reason for this is that cement production is the main source of GHG emissions in the IPPU sector, which occupies approximately 5.00–9.00% of global GHG emissions (Kajaste and Hurme, 2016). Eq. (A. 3) to Eq. (A. 6) in Appendix A show the calculation process.

2.1.3.3. AFOLU. GHG emissions from the AFOLU sector are involved in the following ecosystem components, including biomass, dead organic matter, soils, and livestock. Six sources of GHG emissions from the AFOLU sector are assessed, including CO_2 emissions from urea fertilization, CH_4 emissions from rice cultivation, enteric fermentation, and manure management, and N_2O emissions from manure management and managed soils. Eq. (A. 7) to Eq. (A. 19) in Appendix A show the calculation process.

2.1.4. Monetary valuation of GHG emissions

In environmental studies, results need to be presented in a unified manner to make them comparable and combinative with other economic costs and benefits (Pizzol et al., 2015). To subtract the environmental cost from GDP, an essential process is to convert the environmental impacts of GHG emissions into monetary values through the conversion factor. The monetary valuation of GHG emissions has been extensively investigated (Dong et al., 2019). Following Kunanuntakij et al. (2017), this study adopts the Life-cycle Impact Assessment Method based on Endpoint Modeling to estimate the degradation cost of GHG emissions because it is based on Asian conditions, which is 2.33 yen/kg CO_2. Using Purchasing Power Parities of China and Japan, the cost is transformed into CNY as a conversion factor following Eq. (6):

$$\text{PPP conversion factor } (\text{CNY/JPY})_i = \frac{PPP\ of\ China\ (CNY)_i}{PPP\ of\ Japan\ (JPY)_i} \tag{6}$$

where i is year.

2.2. Data

A mass of data is used to assess China's green GDP. The data sources include the China Statistical Yearbook, the China Industry Statistical Yearbook, the China Energy Statistical Yearbook, the China Agricultural Statistical Report, the China Cement Almanac, the Almanac of the China Building Materials Industry, and others. Table 2 presents the data sources for this study.

Some points deserve special attention. Firstly, as shown in Table 2, this paper uses data from different sources, leading to an inconsistency of statistics caliber. Indeed, as time passes, this problem even appears in the same data source. For instance, the China Statistical Yearbook published the data of output value for 25 industrial sectors in 2015, while it released the same indicator for only 23 industrial sectors in 2010. To keep the statistics caliber consistent, this study splits or merges data from different sources. The China Statistical Yearbook and the China Energy Statistical Yearbook determine that the largest number of sectoral divisions is 27. Table B.1 in Appendix B shows the division of the 27 sectors,

Table 2
Data sources for calculating GHG emissions.

Data	Sources
Output value of 27 sectors	China Statistical Yearbook for the years of 1992–1996, 1999, 2013, 2015, 2018; China Industry Statistical Yearbook for the years of 1997, 1998, 2000–2004, 2006–2008
China's IO tables	China Statistical Yearbook for the years of 1995–1997, 1998, 2003, 2006, 2008, 2010, 2013, 2015, 2018
Final energy consumption	China Energy Statistical Yearbook for the years of 1992–2002, 2004–2017
Annual stock of livestock, and rice planting area	China Agricultural Statistical Report for the years of 1991–2016
Cement production	China Cement Almanac for the years of 2001–2016, excluding 2006; Almanac of China Building Materials Industry for the years of 1992–2006
Production of glass, ammonia, nitric acid, and carbide	China Industry Statistical Yearbook for the year of 2017
Magnesium production	Yearbook of Nonferrous Metals Industry of China for the years of 1992–2017
Urea fertilization	National Agricultural Product Cost-benefit Data Compilation for the years of 1992–2017; China Agricultural Statistical Report for the years of 1991–2016
Areas of cropland organic soils and grassland organic soils	FAO (2019)
Emission factors	IPCC (2006)

Table B.2 in Appendix B displays the merging of different sectors, and Table B.3 in Appendix B shows the splitting process of sectors.

Secondly, there are several processes of dealing with missing data. First, the National Bureau of Statistics of China (NBS) stopped releasing the data of industrial sectors' output value after 2007. However, IO tables in the China Statistical Yearbook contain such data for the years of 2010, 2012, and 2015. Regarding the data in 2008, 2009, 2011, 2013, 2014, and 2016, the total output value of the secondary industry can be obtained from the China Statistical Yearbook. Following the method provided by Zheng et al. (2018), this paper obtains the output value of the 22 industrial sectors in the above-mentioned years. Furthermore, IO tables are the core in the EIO-LCA model. However, NBS only publishes benchmark IO tables in years with the unit digit of 2 or 7 and extended IO tables in years ending with 0 or 5. Currently, there are six benchmark IO tables (1987, 1992, 1997, 2002, 2007, 2012) and six extended IO tables (1990, 1995, 2000, 2005, 2010, 2015). Following the matrix transformation technique method employed by Wang et al. (2015) and Zheng et al. (2018), this study updates China's IO table series for the years of 1991–2016.

Thirdly, this paper covers three kinds of GHG, including CO_2, CH_4, and N_2O. However, different GHG have different global warming potentials. To assess the overall GHG effect, a uniform unit, million tons of carbon dioxide equivalent ($MtCO_2eq$), is adopted, which converts the global warming potentials of CH_4 and N_2O into the potential of CO_2. The global warming potentials for CH_4 and N_2O are 34.00 and 310.00, respectively (Editorial Board of SNARCC, 2011). In other words, the global warming potentials of 1.00 unit of CH_4 or N_2O are equivalent to 34.00 units of CO_2 or 310.00 units of CO_2, respectively.

Fourthly, hydroelectricity, wind electricity, nuclear electricity, and thermal electricity are major types of electricity. The former three are almost carbon-free. Hence, this study only estimates GHG emissions from the generation of thermal electricity. Fifthly, all emission factors used in this study are listed in Table B.4 in Appendix B. Last but not least, the consumer price index is used to eliminate the impact of price fluctuation and the base year is 1991.

3. Results

3.1. Direct GHG emissions

China's total, 27 sectors', and residential sector's direct GHG emissions are calculated based on the 2006 Guidelines and the public data for each sector from NBS. During 1991–2016, China's direct GHG emissions increased from 3,040.60 $MtCO_2eq$ to 10,247.36 $MtCO_2eq$, with an average growth rate of 4.98% per year (see Fig. 3). These results are consistent with Liu et al. (2017), which shows that by 2012, China's total national GHG emissions reached 10,400.00 $MtCO_2eq$. Overall, there are four distinct periods. In the early 1990s, China's total direct GHG emissions increased slowly and steadily, which rose to 3,950.82 $MtCO_2eq$ in 1996. The second period of 1997–1999 witnessed a slight decline in direct GHG emissions. As energy consumption is the main source of GHG emissions in China, this trend is consistent with the decrease in its total energy consumption at that time. The reasons for the falling energy consumption also apply to the descending GHG emissions, which are the statistical underestimation of energy consumption (Wu et al., 2005), the growth in the relative price of energy (Fisher-Vanden et al., 2004), and the increment of energy consumption and efficiency (Wu et al., 2006). Moreover, China's economic slowdown in the late 1990s is also considered as a potential cause (Ouyang and Lin, 2015).

Since 1999, China's economy, especially its industrial sectors, ushered in a period of continuous and rapid growth, making China the world's largest producer of cement, steel, and chemicals. The production of these energy-intensive and GHG-intensive products leads to the dramatic growth of direct GHG emissions. For the years between 1999 and 2013, an annual growth rate of 7.82% augmented China's direct emissions from 3,707.73 $MtCO_2eq$ to 10,641.10 $MtCO_2eq$. The fourth period began in 2014, during which China's direct GHG emissions declined. A similar decreasing trend of GHG emissions is also verified by IEA (2017), which may be driven by a combination of economic slowdown, market dynamics, policy initiatives, and technical progress (Wu et al., 2019b).

Concerning the emission structure, the Manufacturing sector dominates China's direct GHG emissions. In 2016, the proportion of

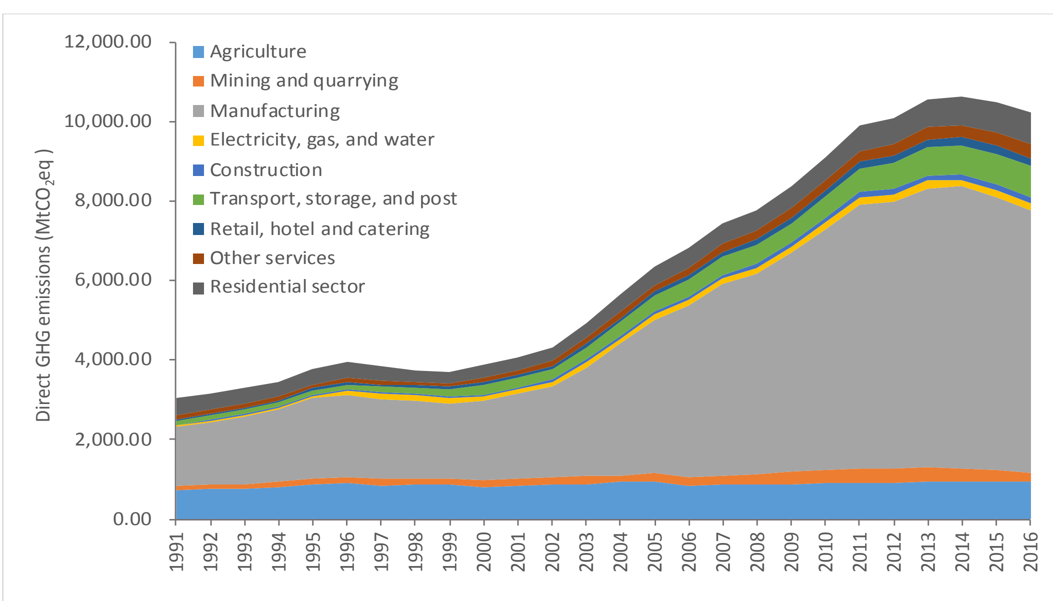

Fig. 3. Direct GHG emissions of eight sectors in China during 1991–2016.

direct GHG emissions in the Manufacturing sector (64.39%) exceeded the sum of all other sectors (35.61%) (see Fig. 4). Direct GHG emissions from the Manufacturing sector ranged between 1,466.59 $MtCO_2eq$ and 6,598.44 $MtCO_2eq$ during 1991–2016, whose ratio to total direct emissions fluctuated between 0.48 and 0.65. Intuitively, the fluctuation trend of the Manufacturing sector's direct GHG emissions was aligned with that of China's direct GHG emissions. Within the Manufacturing sector, nearly 90.00% of CO_2 came from energy consumption, reflecting its characteristics of energy-intensiveness and GHG-intensiveness. GHG emissions from cement production are worth attention as well, which accounted for over 10.00% of the Manufacturing sector's emissions. As the world's largest cement producer, China has raised global concern regarding reducing cement-related CO_2 emissions, since its annual yield accounts for 60.00% of global output (Shen et al., 2017). However, it is predictable that its cement-related CO_2 emissions will be mitigated because the Chinese government has made great efforts to mitigate cement CO_2 emissions in recent years (CCEMENT, 2017), and the slowdown of its urbanization and industrialization will decrease the demand for cement (Shen et al., 2017).

The GHG emissions in the Agriculture sector increased from 737.85 $MtCO_2eq$ in 1991 to 943.35 $MtCO_2eq$ in 2016, while its percentage in China's total direct GHG emissions decreased from 24.27% to 9.21%, which is generally in accordance with the percentage estimated by Nayak et al. (2015) of 11.00%. Within the Agriculture sector, the emissions of four activities exceeded 15.00%, which were managed oil (27.41%), manure management (19.78%), enteric fermentation (19.44%), and energy consumption (18.48%), respectively (see Fig. 4). Overall, China's agricultural GHG emission structure remains essentially constant because the estimation result shown in Fig. 3 is consistent with the result of the National Coordination Committee on Climate Change (2012), which is rice cultivation and managed soil (45.7%) and enteric fermentation and manure management (54.3%) in 2005 without considering GHG emissions from agricultural energy consumption. Although urea application only accounts for 1.37% of agricultural GHG emissions, it deserves special attention because chemical fertilizers are being applied excessively in China and constitute a significant cause of GHG emissions from managed soil. Taking nitrogen fertilizer as an example, its average application rate for rice is 150.00–250.00 kg N/hectare which is 67.00% over the global average (Peng et al., 2010), and its average application rates for wheat and maize are 60.00–150.00% higher than the ideal rate (Norse et al., 2012). A reduction in nitrogen fertilizer can benefit GHG emission mitigation through the channels of both fertilizer application and managed soil (Nayak et al., 2015).

The highest growth rate of GHG emissions was seen in the Transport, storage, and post sector. From 1991 to 2016, GHG emissions from the Transport, storage, and post sector increased from 112.83 $MtCO_2eq$ to 789.68 $MtCO_2eq$, with an average annual growth rate of 8.09%. As China's economy grows, the demand for travel, logistics, and transport services rises, as well (Zhao et al., 2019). Emissions in this sector come from transport activities, such as road, off-road, air, railways, and water-borne navigation. Residential CO_2 emissions were the fastest growing CO_2 emissions in China (Wang and Zhao, 2018). With the improvement in quality of life, significant GHG emission growth has been witnessed in China's Residential sector, which increased from 435.88 $MtCO_2eq$ to 813.36 $MtCO_2eq$.

On closer examination, the nine sectors are subdivided into 27 sectors and the residential sector. Table B.5 in Appendix B shows the direct GHG emissions of China's 27 sectors and residential sector during 1991–2016. In 1991, GHG emissions of six sectors exceeded 100.00 $MtCO_2eq$, which were Agriculture, Residential, Non-metallic mineral, Chemicals, Metal processing, and Transport, storage, and post. Still, these sectors were the top six whose emissions exceeded 500.00 $MtCO_2eq$ in 2016, but the order changed to Metal processing, Non-metallic mineral, Chemicals, Agriculture, Residential, and Transport, storage, and post. The changing order of these sectors is a result of a significant shift in the Chinese economic structure during 1991–2016, which increases its GHG emissions. The cause is that economic structural change from agriculture or light industry to heavy industry augments energy consumption and corresponding GHG emissions (Chen et al., 2018).

GHG emissions of 16 sectors exhibit trends of increasing and then declining, while emissions of 11 sectors display growing

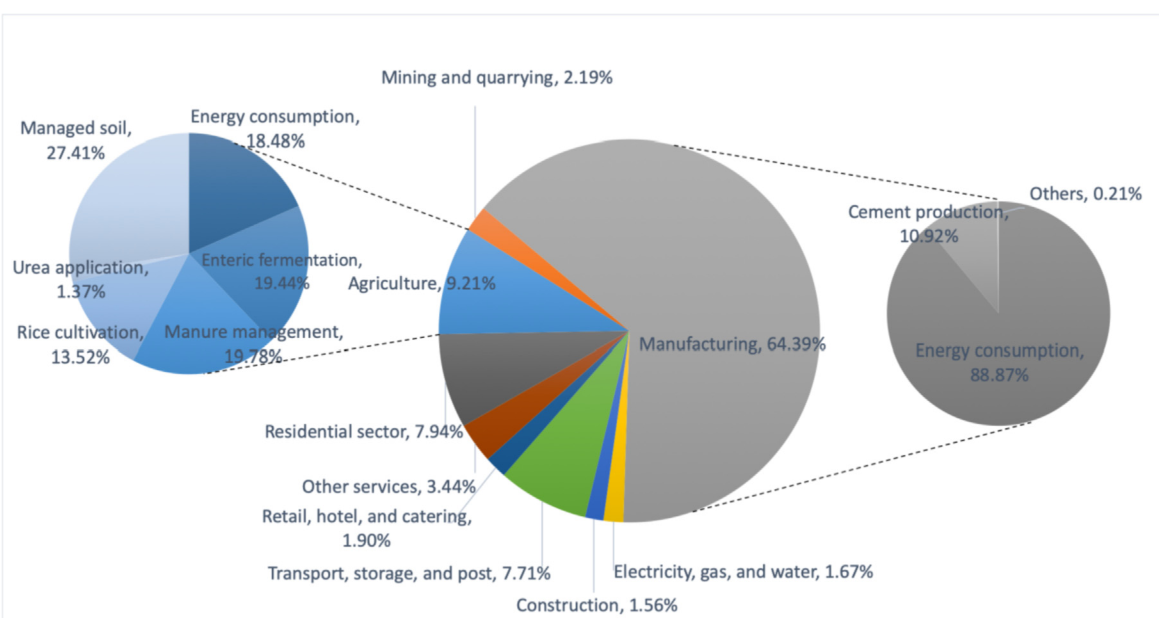

Fig. 4. Structure of China's direct GHG emissions in 2016.

trends. All sectors in the primary and tertiary industries are within the 11 sectors, while all 16 sectors come from the secondary industry. One exception is that the emissions of the Other manufacture sector fell and then rose, which was due to the changes of subsectors within the sector. Of the 28 sectors, the average annual growth rates of 10 sectors' GHG emissions were above the national level, 4.98%, which were Fossil and nuclear fuels (9.68%), Metal processing (9.23%), Transport, storage, and post (8.09%), Electricity, heat, and gas (7.88%), Retail, hotel, and catering (7.69%), Construction (7.40%), Non-metallic mineral (6.84%), Electronic equipment (5.81%), Water (5.72%), and Other services (5.68%).

When considering both GHG emissions and growth trends, some brief conclusions can be reached. First, direct GHG emissions among different sectors reveal China's rapid industrialization process from 1991 to 2016, as both GHG emissions and their growth rates of most industrial sectors were more extensive and higher than those of the sectors in the primary and tertiary industries. Second, China's economic transformation and new growth pattern are promising as the declining trends of GHG emissions in the secondary industry are observed, while the trends in the primary and tertiary industries are rising. Third, the peak of China's direct GHG emissions has probably passed. Intuitively, both the total direct GHG emissions and direct GHG emissions of most industrial sectors stagnated or even began to fall (see Fig. 3 and Table B.5 in Appendix B). Peng et al. (2018b) and Wu et al. (2019b) also verified similar trends, and possible reasons are China's economic slowdown and improved energy efficiency.

3.2. Total GHG emissions

All sectors within an economic system are interconnected, and one sector's products or services are inputs for itself and other sectors, such as raw material, energy production or transportation, leading to the flow of their environmental impacts among different sectors and in various life phases (Gan and Griffin, 2018). The assessment of total GHG emissions throughout an output's life cycle in every sector covers raw material acquisition, production, distribution, use, and end-of-life phases (Finnveden et al., 2009). Since the existing data are insufficient to clearly distinguish all life phases of products and services in every sector, this paper considers the total GHG emissions of each sector individually. Consequently, some overlaps of GHG emissions exist among these 27 sectors, which, however, does not influence the investigation of GHG emissions in each sector. Based on the EIO-LCA model, 27 sectors' total GHG emissions from the cradle to the grave are calculated using the IO tables, excluding the Residential sector.

Table B.6 in Appendix B shows 27 sectors' total GHG emissions during 1991–2016. Total GHG emissions in eight sectors rose first and then fell, while emissions of 15 sectors kept growing. Moreover, although the fluctuations of GHG emissions in the remaining four sectors were drastic, the emissions remained unchanged at the beginning and end of this period. Specifically, GHG emissions of four sectors exceeded 1,000.00 $MtCO_2eq$ in 1991, including Non-metallic mineral, Chemicals, Metal processing, and Agriculture; whereas, in 2016, emissions of six sectors exceeded 1,000.00 $MtCO_2eq$, which were Metal processing, Non-metallic mineral, Chemicals, Transport, storage, and post, Agriculture, and Fossil and nuclear fuels. Among the 27 sectors, the average annual growth rates of eight sectors' GHG emissions were over the national level, 7.26%, which were Metal processing (11.80%), Fossil and nuclear fuels (11.01%), Electricity, heat, and gas (11.00%), Water (10.73%), Transport, storage, and post (10.25%), Construction (8.64%), Retail, hotel, and catering (7.40%), and Electronic equipment (7.27%). Furthermore, negative growth was observed in Other manufacture, which decreased from 193.48 $MtCO_2eq$ in 1993 to 84.92 $MtCO_2eq$ in 2016.

Outputs from different sectors have different life cycles, leading to variance of their total and indirect GHG emissions (Kunanuntakij et al., 2017). The proportions of direct GHG emissions to total GHG emissions in most sectors decreased from 1991 to 2016, excluding Petroleum and gas extraction, Nonmetal ores, Leather, Wood products, and Retail, hotel, and catering (see Table B.5 and Table B.6 in Appendix B). Specifically, the proportion of the national level was 34.45% in 1991, which decreased to 20.82% in 2016. In 1991, Agriculture (65.89%), Other services (62.92%), Petroleum and gas extraction (62.90%), and Transport, storage, and post (60.41%) were four sectors with a proportion higher than 60.00%; whereas, in 2016, Petroleum and gas extraction (94.32%), Retail, hotel, and catering (56.79%), Agriculture (56.77%), and Other services (55.84%) were four sectors with a proportion higher than 50.00%. However, the reasons for the decrease in these top sectors vary. Agriculture sector is used here as an example for illustration purpose. China's Agriculture sector has long been characterized by self-sufficient and small-scale farming (Ren et al., 2019), leading to low dependence on raw materials or services from other sectors. Policies, including the grain crop subsidy, the incentive scheme for grain-producing regions, and nurturing new agricultural units have significantly promoted farmland consolidation and concentration (Zhan, 2017), which influences the proportion in two ways. First, large-scale operations can adopt more factor inputs from other sectors that are unaffordable for small operation units, such as agricultural machinery. Secondly, the rising farming operation scale improves input use efficiency by decreasing the use of fertilizer and energy, thereby reducing the proportion of direct GHG emissions in the Agriculture sector (Zhu et al., 2018).

3.3. Green GDP

The EIO-LCA model originates from the idea of Leontief (1970) that "pollution and other undesirable-or desirable-external effects of productive or consumptive activities should for all practical purposes be considered part of the economic system." China's green GDP is calculated by subtracting the environmental costs of GHG emissions from GDP. As is shown in Fig. 5, China's GDP increased from 2,060.17 billion CNY in 1991 to 26,516.84 billion CNY in 2016, constituting an increase of approximately 13.00 times. Correspondingly, the environmental cost of GHG emissions increased from 56.29 billion CNY to 271.59 billion CNY. Indeed, the two codetermine the growth of green GDP from 2,003.88 billion CNY to 26,245.25 billion CNY. Although the environmental cost of GHG emissions in China kept rising, its proportion to the traditional GDP fell, from 2.73% to 1.02% during 1991–2016, reflecting the decreasing intensity of GHG emissions. This result is in accordance with Liu et al. (2012), Ouyang and Lin (2015), and Peng et al. (2018b). The underlying factors for the reduction include GDP per capita, technical progress, foreign direct investments, and energy prices (Gui et al., 2017).

An investigation into the sectoral green output value assists to evaluate the sustainability of 27 sectors' economic growth. Fig. 6 displays the output value and green output value of China's 27 sectors during 1991–2016. There are two overall trends worthy of attention. First, the trends of fluctuation in output value and green output value exhibited a high degree of consistency. Overall, both the output value and green output value in most sectors grew during the investigation period, except Coal mining, Petroleum and gas extraction, Metal ores, Nonmetal ores, Metal processing, and Other manufacture. These exceptions can be explained by China's actions of cutting overcapacity in these sectors. China's economy has stepped into a new normal phase since 2013, and one distinct feature of this is restructuring, which aims to increase the

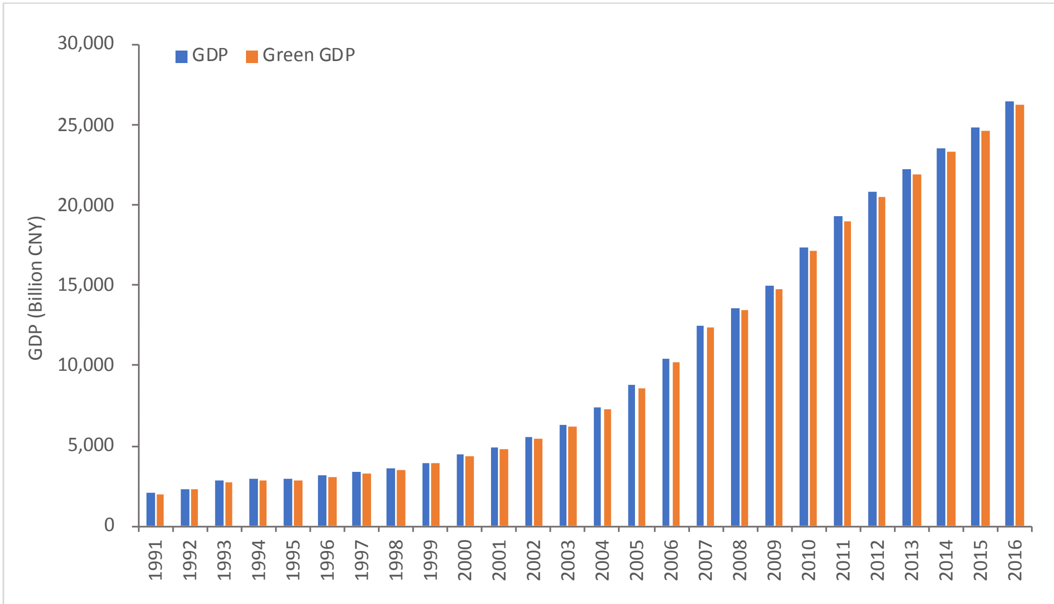

Fig. 5. China's GDP and green GDP considering the environmental cost of GHG emissions during 1991–2016.

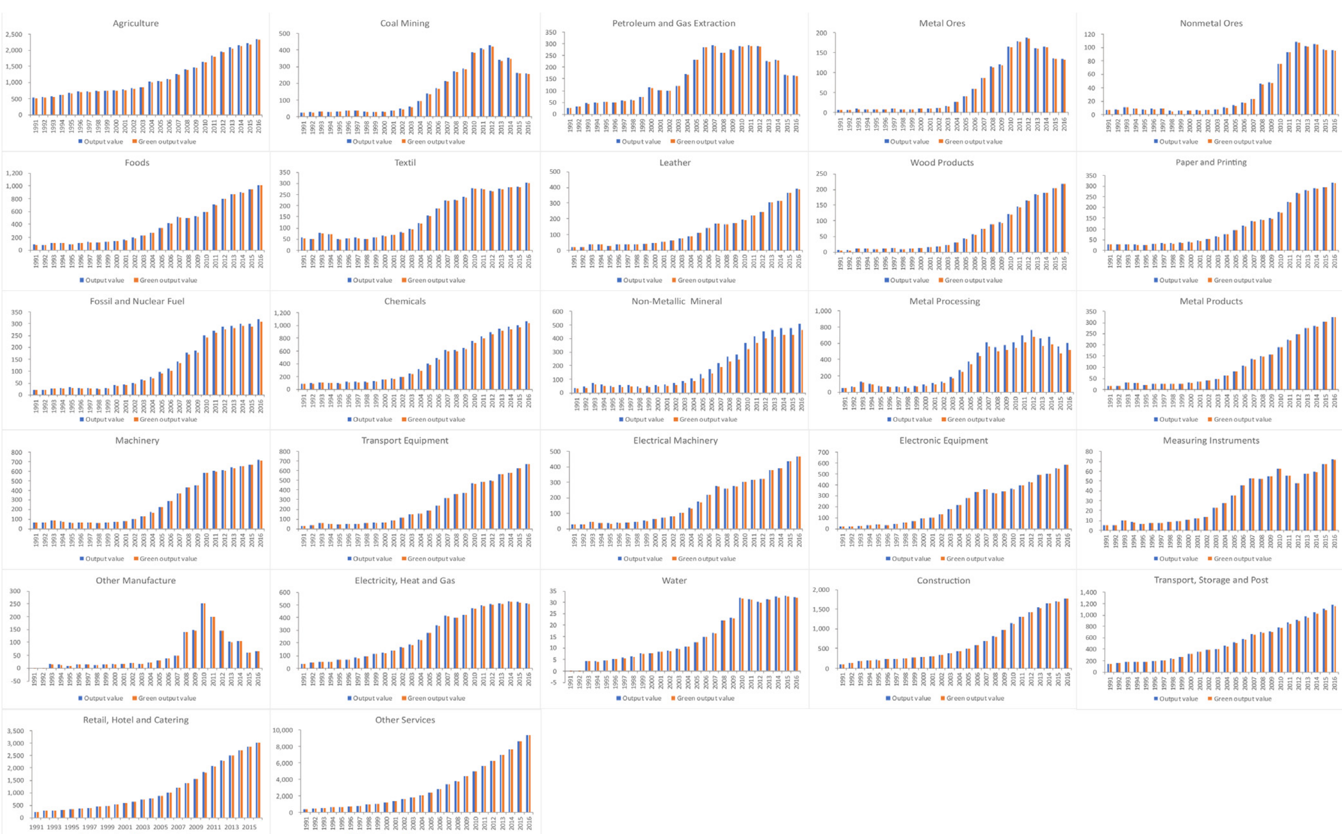

Fig. 6. Output value and green output value considering the environmental cost of GHG emissions of China's 27 sectors during 1991–2016 (billion CNY).

proportions of high-tech industries and services and decrease energy consumption (Chen and Groenewold, 2018). Most of the sectors mentioned above belong to the Mining and quarrying sector, which is related to mining and washing of coal, extraction of petroleum and natural gas, mining and processing of metal ores, and mining and processing of nonmetal ores and other ores. The phenomenon of supply exceeding demand is common for many industrial products, such as coal, cement, plate glass, and crude steel (Wu et al., 2019b), resulting in a decline of output value in the sectors providing raw industrial materials. For example, China's coal output decreased for three consecutive years after reaching the peaking point of 3.97 Mt in 2013, and little growth occurred in the most recent two years (NBS, 2019b).

Second, the proportion of GHG-related cost in the sectoral output value revealed decreasing trends in most sectors, which reflects effective sectoral GHG emission mitigation. In 1991, the proportion in six sectors was within 1.00%, including Electrical machinery, Electronic equipment, Leather, Construction, Other services, and Retail, hotel, and catering, and the proportion in two sectors was over 10.00%, which were Non-metallic mineral and Metal processing. In 2016, the proportion was within 1.00% in 19 sectors and was within 5.00% in six sectors. However, the proportion in 2016 still exceeded 5.00% in two sectors, which were the Non-metallic mineral sector and the Metal processing sector. It can be seen that great achievements in sectoral GHG emission mitigation have been made in China. Similar results are observed in many sectoral studies, such as the Electric power sector (Feng et al., 2019), the Textile sector (Huang et al., 2017), the Construction sector (Du et al., 2019), etc.

The Non-metallic mineral sector and the Metal processing sector deserve additional attention because they have been more carbon-intensive than other sectors during 1991–2016. Although the proportion in the Non-metallic mineral sector decreases from 21.35% in 1991 to 8.98% in 2016, it is only after the proportion of the Metal processing sector in 2016. The Non-metallic mineral sector consists of the manufacture of cement, lime, plaster, bricks, glass, fiberglass, ceramic, refractory matters, graphite, and related products (State Administration for Market Regulation and Standardization Administration, 2017). Driven by large-scale infrastructure construction and housing due to rapid urbanization, China's demand for these products is enormous (Lin and Ouyang, 2014). As a pillar industry in China, the Non-metallic mineral sector is responsible for 9.50% of national, 13.50% of industrial, and 16.45% of the manufacture of energy consumption in China (Lin and Ouyang, 2014). More importantly, its energy consumption structure is dominated by coal, leading to the growth of GHG emissions. However, the downward trend is a result of the Chinese government's efforts to mitigate CO_2 emissions (CCEMENT, 2017), as well as the slowdown of its urbanization and industrialization (Shen et al., 2017).

In the Metal processing sector, the proportion increases from 12.48% in 1991 to 14.20% in 2016. The significant differences are a result of the decline in China's ores' quality. As the world's biggest crude steel producer and consumer, China accounts for 50.40% of global production, as well as 43.60% of global consumption (Editorial Board of the China Steel Yearbook, 2016). This huge demand results in over-exploitation of iron ore resources and increasing use of low-quality ores (Gan and Griffin, 2018). During 2006–2012, the iron content of China's produced crude ore descends from 30.00% to 27.00% (Editorial Board of the China Steel Yearbook, 2014). Consequently, additional energy is requisite to obtain an equivalent mass of metal concentrate with low-quality iron ores, which results in the enhancement of GHG emission intensity (Norgate and Haque, 2010).

During the whole investigation period, the difference has been within 1.00% in sectors, including Leather (0.17–0.83%), Electrical machinery (0.19–0.94%), Electronic equipment (0.15–0.90%), Construction (0.19–0.57%), Retail, hotel, and catering (0.19–0.31%), and Other services (0.12–0.49%) and is within 5.00% in sectors, including Agriculture (1.24–2.98%), Petroleum and gas extraction (0.47–2.09%), Metal ores (0.85–3.70%), Foods (0.54–2.32%), Textile (0.87–2.99%), Wood products (0.44–3.47%), Paper and printing (0.77–4.46%), Metal products (0.52–2.28%), Machinery (0.36–2.12%), Transport equipment (0.23–1.86%), Measuring instruments (0.15–1.14%), Electricity, heat, and gas (0.82–3.05%), Water (0.82–1.87%), and Transport, storage, and post (1.29–2.20%). The low proportions of the differences in these sectors reveal their low GHG emission intensity.

4. Discussion and policy implications

According to the Ministry of Ecology and Environment of China (MEE), China accomplished a reduction of 46.00% below the 2005 carbon intensity in 2017, which implies that it achieved the reduction target of 40.00–45.00% three years ahead of schedule (MEE, 2018). However, China remains the largest energy consumer and the biggest GHG emitter worldwide (Zhao et al., 2019). As China's economy has entered a new normal phase of industrial restructuring since 2013, substantial sectoral disparities of GHG emissions and corresponding environmental costs necessitate special attention. The estimation results shed light on its GHG mitigation policies and supply-side structural reform in the following aspects.

The estimation results reveal that most of China's GHG emissions come from the secondary industry, and the gaps between GDP and green GDP in traditional energy-intensive and GHG-intensive industrial sectors enlarge, such as Metal pressing and Non-metallic mineral, while that in some new industries, such as Electronic equipment and Electrical machinery, falls. However, these industrial sectors still account for a significant proportion of China's secondary industry, and it is found that the industrial structure dominated by these industries increases GHG emissions and corresponding cost (Wu et al., 2019b). Hence, more attention should be paid to the internal restructuring of the industrial sectors. The finding is consistent with the results of Zhang et al. (2018) that restructuring the industrial sectors has a greater reduction potential than restructuring the three main industries during the five five-year plan periods. Similarly, the contribution rate of restructuring the industrial sectors to GHG emissions is projected to increase (Zhang et al., 2018), which is consistent with this study. Consequently, it is suggested to formulate policies to revise the directory of guidance for industrial restructuring, set standards for GHG emissions in key sectors, such as Metal pressing and Non-metallic mineral, promote new technologies to upgrade traditional manufacturing sectors, and speed up the elimination of outdated production capacity.

It is also necessary to adjust the energy structure in China. The primary source of GHG emissions is energy consumption, and most sectors' energy consumption structure is dominated by coal. To reduce GHG emissions, the proportion of coal in China's energy should be gradually reduced. Compared to fossil fuels, renewable energy sources, including solar energy, wind energy, biomass energy, and geothermal energy, are renewable and eco-friendly. According to the estimation of Squalli (2017), a 10% increase in the share of renewable energy lowers CH_4 emissions by approximately 0.26%. However, the adoption of new energy manufacturing technologies often requires high initial costs and raises process complexity, which hinders the wide adoption of renewable energy in industrial sectors (Hanes et al., 2019). Hence, more policy resources should move towards the development and application of green energy in industrial sectors, including renewable energy consumption subsidies and funds for the application of renewable energy technology in industrial sectors.

Some sectors' GHG emission mitigation in the primary and tertiary industries is worthy of attention, as well, especially the Agriculture sector and the Transport, storage, and post sector. While both direct and total GHG emissions from some industrial sectors began to fall, there is no downward trend in the primary and tertiary industry. In the Agriculture sector, GHG emissions from energy consumption only account for 18.48% of total emissions (see Fig. 4). However, the Chinese government has proposed to achieve agricultural modernization by 2035 (CCCPC and SC, 2018), which is characterized by agricultural mechanization and increasing utilization of chemicals. For instance, the Chinese government proposed to augment the overall mechanization rate of tillage and harvest for wheat, rice, and corn to over 80.00% and improve the total power of agricultural machinery to 1,200.00 million kilowatts by 2020 (Han and Wu, 2018), which will lead to the growth of energy consumption and corresponding GHG emissions. Hence, measures relating to other sources of agricultural GHG emissions can be adopted, such as the selection of fertilizer type. According to Wang et al. (2017), the judicious selection of fertilizer type would be conductive to mitigate agricultural GHG emissions in China, such as ammonium bicarbonate, calcium superphosphate, and potassium chloride. As a result, it is suggested to promote soil testing and fertilizer recommendation technology nationwide, substitute organic for chemical fertilizers, and upgrade traditional agricultural machinery in the Agriculture sector.

China's economy has also entered a new normal phase of industrial restructuring to increase the share of tertiary industry and high-tech industrial sectors. The tertiary industry deserves more attention because though it emits less GHG than the secondary industry, its emission sources are more dispersed and the volume is soaring (Zhang et al., 2018). Consequently, both its emission volume and share in total emission will continue to grow. However, what should be pointed out is that restructuring towards the tertiary sector contributes to GHG emission reduction. For instance, it is found that a 1.00% increase in the tertiary industry's share in GDP contributes to a 0.76% decrease in CO_2 emissions in Shanghai city (Yang et al., 2018). Specifically, driven by fast economic growth, it is projected that China's vehicle stock will rise to 543.00 million by 2050, resulting in significant growth in energy consumption and GHG emissions in the Transport, storage, and post sector (Peng et al., 2018a). A combination of these factors will lead to further growth of GHG emissions from the primary and tertiary industries. Hence, it is suggested to optimize logistics systems, use new-energy vehicles, and tighten fuel consumption and emission regulations in the Transport, storage, and post sector.

5. Conclusions

Based on the SEEA and using the EIO-LCA, this study calculates the green GDP and green output value of 27 sectors to reflect the environmental costs of GHG emissions in China during 1991–2016. The findings are as follows. Firstly, while China's direct GHG emissions increased from 3,040.60 $MtCO_2eq$ to 10,641.10 $MtCO_2eq$ during 1991–2014, declining trends were observed in China's total and 16 sectors' direct GHG emissions in the subsequent two years. Among the sectors, Metal processing, Non-metallic mineral, Chemicals, Agriculture, Residential, and Transport, storage, and post have been the top six emitters during the whole investigation period, whose emissions were 2,954.76 $MtCO_2eq$, 1,582.80 $MtCO_2eq$, 1,105.69 $MtCO_2eq$, 943.35 $MtCO_2eq$, 813.36 $MtCO_2eq$, and 789.66 $MtCO_2eq$ in 2016, respectively. Secondly, total GHG emissions in eight sectors rose first and then fell, while the emissions of 15 sectors continued to grow. Different life cycles of outputs from different sectors lead to the variance of their total or indirect GHG emissions, and thereby cause the differences between sectoral direct and total GHG emissions. The ratios of direct GHG emissions to total GHG emissions in most sectors decreased, reflecting the increasing interdependence among these sectors. Thirdly, China's green GDP grew from 2,003.88 billion CNY to 26,245.25 billion CNY during 1991–2016, and the difference between China's GDP and green GDP decreased from 2.73% to 1.02%. The decreasing gap between the output value and green output value has also been seen in more than 20 sectors. Furthermore, the trends of fluctuation in output value and green output value exhibit a high degree of consistency, which is rising in most sectors.

The results provide some implications that possibly shed light on the revival of China's green accounting system, GHG mitigation policies, and supply-side structural reform. The policy implications include: (1) formulating policies to revise the directory of guidance for industrial restructuring, setting standards for GHG emissions in key sectors, such as Metal pressing and Non-metallic mineral, promoting new technologies to upgrade traditional manufacturing sectors, and speeding up the elimination of outdated production capacity; (2) allocating more policy resources to the development and application of green energy in industrial sectors; (3) promoting soil testing and fertilizer recommendation technology nationwide, substituting organic for chemical fertilizers, and upgrading traditional agricultural machinery in the Agriculture sector, and optimizing logistics systems, using new-energy vehicles, and tightening fuel consumption and emission regulations in the Transport, storage, and post sector.

Future research work should try to enlarge the scope and improve the accuracy of the results obtained in two aspects. Firstly, more GHG emission sources should be included when data is available. Due to data unavailability, not all GHG emission sources covered by the 2006 IPCC Guidelines are included in this paper, such as sulfur hexafluoride and perfluorocarbons emitted from the manufacture and use of electrical equipment. Secondly, more investigation should be conducted to determine the China-specific emission factor method. Due to lacking China-specific emission factor information, this paper adopts the default emission factor method rather than the China-specific emission factor method. Besides, future research could focus on the impacts of climate change policies on GHG emissions because the Chinese government has spared no efforts to mitigate climate change and its effects should be examined.

Declaration of competing interest

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

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Appendix A

Energy

The estimation of GHG emissions from fuel combustion is as follows:

$$Emissions_{GHG,\,fuel} = Fuel\ Combustion_{fuel} * Emission\ Factor_{GHG,\,fuel} \tag{A1}$$

where $Emissions_{GHG,\,fuel}$ are emissions of a given GHG by type of fuel, $Fuel\ Combustion_{fuel}$ is the amount of fuel combusted, and $Emission\ Factor_{GHG,\,fuel}$ is the default emissions of a given GHG by type of fuel. It is assumed that all energy is utilized through combustion because energy utilized in other channels only accounts for a tiny proportion of total energy use. More importantly, China's energy statistics do not differentiate energy used through combustion from that used through other channels.

The calculation of fugitive GHG emissions is as follows:

$$Emissions_{GHG,\ fuel} = Emission\ Factor_{GHG,\ fuel} * Fuel\ Production_{fuel} * Conversion\ Factor \tag{A2}$$

where $Fuel\ Production_{fuel}$ is the production of fuel, and *Conversion Factor* is the density of $CO_2/CH_4/N_2O$ and converts their volume to the mass.

IPPU

In cement manufacture, CO_2 release is induced by energy consumption and clinker production. The energy-related CO_2 emissions are estimated in the Energy part, and this part only focuses on process-related emissions. Clinker is the primary intermediate product for cement production, which is obtained through melting a mixture of limestone, clay, and sand. CO_2 is generated in the melting process, which contributes to 90.00–95.00% of CO_2 emissions in the whole cement production process (Mikulčić et al., 2013). The calculation of process-related CO_2 emissions from cement production is given as:

$$CO_2\ Emissions = \left[\sum_i (M_{ci} * C_{cli}) - Im + Ex\right] * EF_{clc} \tag{A3}$$

where M_{ci} is the weight of cement of type i, C_{cli} is the clinker fraction of cement of type i, Im is the import for consumption of clinker, Ex is the export of clinker, and EF_{clc} is the emission factor for clinker of the particular cement.

The calculation of CO_2 emissions from glass production is as follows:

$$CO_2\ Emissions = M_g * EF * (1 - CR) \tag{A4}$$

where M_g is the mass of glass produced, EF is the default emission factor for manufacturing glass, and CR is the cullet ratio in the production process.

The calculation of N_2O emissions from nitric acid production is given as:

$$N_2O\ Emissions = EF * NAP \tag{A5}$$

where EF is the N_2O emission factor, and NAP is the nitric acid production.

The calculation of CO_2 emissions from magnesium production is as follows:

$$CO_2\ Emissions = (P_d * EF_d + P_{mg} * EF_{mg}) * 10^{-3} \tag{A6}$$

where P_d is the national main magnesium from dolomite, P_{mg} is the national primary magnesium production from magnesite, EF_d is the default emission factor for CO_2 emissions from primary magnesium production from dolomite, and EF_{mg} is the default emission factor for CO_2 emissions from magnesium production from magnesite.

AFOLU

The application of chemicals is a crucial factor in modern agriculture (Han and Wu, 2018). During the fertilization process, urea breaks down into ammonium, hydroxyl ion, and bicarbonate, and then, bicarbonate converts into water and CO_2. The calculation of annual CO_2 emissions from urea fertilization is given as:

$$CO_2 - C\ \text{Emissions} = \text{M} * \text{EF} \tag{A7}$$

where $CO_2 - C$ is the annual carbon emissions from urea fertilization, M is the annual amount of urea fertilization, and EF is the emission factor.

Rice cultivation is a significant source of CH_4 (Jeong et al., 2018), which produces CH_4 through the anaerobic decomposition of soil organic material in water-irrigated rice fields (Nouchi et al., 1990). China is the world's second-largest rice planter and has a sown area of 301.78 million hectares. The calculation of CH_4 emissions from rice cultivation is as follows:

$$CH_{4\ Rice} = \sum_{i,j,k} \left(EF_{i,j,k} * t_{i,j,k} * A_{i,j,k} * 10^{-6}\right) \tag{A8}$$

where $CH_{4\ Rice}$ is the annual CH_4 emissions from rice cultivation, $EF_{i,j,k}$ is the daily emission factors for i, j, and k conditions, $t_{i,j,k}$ is the cultivation periods of rice for i, j, and k conditions, and $A_{i,j,k}$ is the harvested areas of rice per year for i, j, and k conditions.

Livestock production has long been recognized as an important source of GHG emissions (de Souza Filho et al., 2019). Only CH_4 emissions from enteric fermentation and manure management are estimated because plants' photosynthesis process absorbs the respired CO_2 from livestock (IPCC, 2006). The calculation of CH_4 from enteric fermentation is given as:

$$CH_{4\ Enteric\ fermentation} = ET_{(T)} * \left(\frac{N_{(T)}}{10^6}\right) \tag{A9}$$

$$Total\ CH_4 = \sum_i E_i \tag{A10}$$

where $CH_{4\ Enteric\ fermentation}$ is the CH_4 emissions from enteric fermentation, $ET_{(T)}$ is the emission factor for the defined livestock population, $N_{(T)}$ is the number of head of livestock species/category T, and E_i is the emissions for the i^{th} livestock categories and subcategories. In China, dairy cattle, buffalo and other cattle, horses, donkeys, mules, camels, hogs, goats, and sheep constitute the main livestock. The calculation of CH_4 emissions from manure management is as follows:

$$CH_{4\ Manure} = \sum_{(T)} \frac{(EF_{(T)} * N_{(T)})}{10^6} \tag{A11}$$

where $CH_{4\ Manure}$ is CH_4 emissions from manure management, $EF_{(T)}$ is the emission factor, and $N_{(T)}$ is the number of head of livestock species/category T. In addition, N_2O is emitted both directly and indirectly from manure management. Direct N_2O emissions are caused by combined nitrification and denitrification of nitrogen contained in the manure. Indirect emissions occur due to volatile nitrogen losses, which are primarily in the forms of ammonia and NO_x. The calculation of direct and indirect N_2O emissions from manure management follows Eq. (18) and Eq. (19), respectively:

$$N_2O_{D(mm)} = \left[\sum_S \left[\sum_T \left(N_{(T)} * Nex_{(T)} * MS_{(T,S)}\right)\right] * EF_{3(S)}\right] * \frac{44}{28} \tag{A12}$$

$$N_{volatilization-MMS} = \sum_{S}\left[\sum_{T}\left[\times \left(N_{(T)} * Nex_{(T)} * MS_{(T,S)}\right) * \left(\frac{Frac_{GasMS}}{100}\right)_{(T,S)}\right]\right] \quad \text{(A13)}$$

where $N_2O_{D(mm)}$ is direct N_2O emissions from manure management, $N_{(T)}$ is the number of head of livestock species/category T, $Nex_{(T)}$ is the annual average N excretion per head of species/category T, $MS_{(T,S)}$ is the fraction of total annual nitrogen excretion for each livestock species/category T that is managed in manure management system S, $EF_{3(S)}$ is the emission factor for direct N_2O emissions from manure management system S, $N_{volatilization-MMS}$ is the amount of manure nitrogen that is lost due to volatilization of NH_3 and NO_x, and $Frac_{GasMS}$ is the percentage of managed manure nitrogen for livestock category that volatilizes as NH_3 and NO_x.

In the process of soil management, human-induced nitrogen conditions or adjustment of land-use and/or management practices often enhance available nitrogen, which, subsequently, increases N_2O emissions through nitrification and denitrification. The calculation of direct N_2O emissions from managed soils follows Eq. (20)–(23):

$$N_2O_{Direct} - N = N_2O - N_{N\ input} + N_2O - N_{OS} + N_2O - N_{PRP} \quad \text{(A14)}$$

$$N_2O - N_{N\ input} = [(F_{SN} + F_{ON} + F_{CR} + F_{SOM}) * EF_1 + (F_{SN} + F_{ON} + F_{CR} + F_{SOM})_{FR} * EF_{1FR}] \quad \text{(A15)}$$

$$N_2O - N_{OS} = \left(F_{OS,CG,Temp} * EF_{2CG,Temp}\right) + \left(F_{OS,CG,Trop} * EF_{2CG,Trop}\right) + \left(F_{OS,F,Temp,NR} * EF_{2F,Temp,NR}\right) + \left(F_{OS,F,Temp,NP} * EF_{2F,Temp,NP}\right) + \left(F_{OS,F,Trop} * EF_{2F,Trop}\right) \quad \text{(A16)}$$

$$N_2O - N_{PRP} = \left[\left(F_{PRP,CPP} * EF_{3PRP,CPP}\right) + \left(F_{PRP,SO} * EF_{3PRP,SO}\right)\right] \quad \text{(A17)}$$

where $N_2O_{Direct} - N$ is the annual direct nitrogen emissions produced from managed soils, $N_2O - N_{N\ input}$ is the annual direct nitrogen emission from nitrogen inputs to managed soils, $N_2O - N_{OS}$ is the direct nitrogen emissions from managed organic soils, $N_2O - N_{PRP}$ is the annual direct nitrogen emissions from urine and dung inputs to grazed soils, F_{SN} is the annual amount of synthetic fertilizer nitrogen applied to soils, F_{ON} is the annual amount of animal manure, compost, sewage sludge, and other organic nitrogen additions applied to soils, F_{CR} is the annual amount of nitrogen in crop residues, F_{SOM} is the annual amount of nitrogen in mineral soils that is mineralized, F_{OS} is the annual area of managed/drained organic soils, F_{PRP} is the annual amount of urine and dung nitrogen deposited by animals, EF_1 is the emission factor for N_2O emissions from nitrogen inputs, EF_{1FR} is the emission factor for N_2O emissions from nitrogen inputs to flooded rice, EF_2 is the emission factor for N_2O emissions from drained/managed organic soils, and EF_{3PRP} is the emission factor for N_2O emissions from urine and dung nitrogen. The calculation of indirect N_2O emissions from managed soils follows Eq. (24) and Eq. (25):

$$N_2O_{(ATD)} - N = [(F_{SN} * Frac_{GASF}) + ((F_{ON} + F_{PRP}) * Frac_{GASM})]*EF_4 \quad \text{(A18)}$$

$$N_2O_{(L)} - N = (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM})*Frac_{LEACH-(H)}*EF_5 \quad \text{(A19)}$$

where $N_2O_{(ATD)} - N$ is the annual amount of nitrogen from atmospheric deposition of nitrogen volatilized from managed soils, $Frac_{GASF}$ is the fraction of synthetic fertilizer nitrogen applied to soils, $Frac_{GASM}$ is the fraction of applied organic nitrogen fertilizer materials and of urine and dung, EF_4 is the emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces, $N_2O_{(L)} - N$ is the annual amount of nitrogen from leaching and runoff of nitrogen additions to soils, $Frac_{LEACH-(H)}$ is the fraction of all nitrogen added to/mineralized in managed soils, and EF_5 is the emission factor for N_2O emissions from nitrogen leaching and runoff.

Appendix B

Table B.1
The division of 27 sectors.

Industry division	Industry subdivision			Abbreviation
Primary industry	Farming, forestry, animal husbandry, and fishery			Agriculture
Secondary industry	Industry	Mining and quarrying	Mining and washing of coal	Coal mining
			Extraction of petroleum and natural gas	Petroleum and gas extraction
			Mining and processing of metal ores	Metal ores
			Mining and processing of nonmetal ores and other ores	Nonmetal ores
		Manufacturing	Processing of food from agricultural products and manufacture of foods and liquor, beverages, and refined tea and tobacco	Foods
			Manufacture of textile	Textile
			Manufacture of textile, wearing apparel, accessories and leather, fur, feather, and related products and footwear	Leather
			Processing of timber, manufacture of wood, bamboo, rattan, palm, straw products, and manufacture of furniture	Wood products
			Manufacture of paper and paper products, and printing and reproduction of recording media and manufacture of articles for culture, education, arts and crafts, and sport and entertainment activities	Paper and printing
			Processing of petroleum, coking, and processing of nuclear fuels	Fossil and nuclear fuels
			Manufacture of raw chemical materials and chemical products, and medicines, chemical fibers, and rubber and plastics products	chemicals
			Manufacture of non-metallic mineral products	Non-metallic mineral
			Smelting and pressing of metals	Metal processing
			Manufacture of metal products	Metal products

(continued on next page)

Table B.1 (*continued*)

Industry division	Industry subdivision			Abbreviation
			Manufacture of general-purpose machinery and special-purpose machinery	Machinery
			Manufacture of automobiles and railway, ships, aerospace, and other transport equipment	Transport equipment
			Manufacture of electrical machinery and apparatus	Electrical machinery
			Manufacture of computers, communication, and other electronic equipment	Electronic equipment
			Manufacture of measuring instruments and machinery	Measuring instruments
			Other manufacture and utilization of waste resources	Other manufacture
		Electricity, gas, and water	Production and supply of electric power and heat power, and gas	Electricity, heat, and gas
			production and supply of water	Water
	Construction			Construction
Tertiary industry	Transport, storage, and post			Transport, storage, and post
	Retail, hotel, and catering			Retail, hotel, and catering
	Other services			Other services

Table B.2
Merging of sectors.

Sector	1991–1992	1993–1995	1996–2002
Agriculture	Farming, forestry, animal husbandry, and fishery	Farming, forestry, animal husbandry, and fishery	Farming, forestry, animal husbandry, and fishery
Coal mining	Mining of coal and lignite	Mining of coal and lignite	Mining of coal and lignite
Petroleum and gas extraction	Extraction of crude petroleum and natural gas	Extraction of crude petroleum and natural gas	Extraction of crude petroleum and natural gas
Metal ores	Mining of ferrous metal ores	Mining of ferrous metal ores	Mining of ferrous metal ores
	Mining of nonferrous metals ores	Mining of nonferrous metals ores	Mining of nonferrous metals ores
Nonmetal ores	Mining of nonmetal ores	Mining of nonmetal ores	Mining of nonmetal ores
	Mining of other ores	Mining of other ores	
	Mining of salt ores		
Foods	Manufacture of food products	Processing of food products	Processing of food products
	Manufacture of beverages	Manufacture of food products	Manufacture of food products
	Manufacture of tobacco products	Manufacture of beverages	Manufacture of beverages
		Manufacture of tobacco products	Manufacture of tobacco products
Textile	Manufacture of textiles	Manufacture of textiles	Manufacture of textiles
Leather	Manufacture of wearing apparel	Manufacture of wearing apparel	Manufacture of wearing apparel
	Manufacture of leather and related products	Manufacture of leather and related products	Manufacture of leather and related products
Wood products	Manufacture of wood and of products of wood and cork, articles of straw, and plaiting materials	Manufacture of wood and of products of wood and cork, articles of straw, and plaiting materials	Manufacture of wood and of products of wood and cork, articles of straw, and plaiting materials
	Manufacture of furniture	Manufacture of furniture	Manufacture of furniture
Paper and printing	Manufacture of paper and paper products	Manufacture of paper and paper products	Manufacture of paper and paper products
	Printing and reproduction of recorded media	Printing and reproduction of recorded media	Printing and reproduction of recorded media
	Manufacture of musical instruments, sports goods, games, and toys	Manufacture of musical instruments, sports goods, games, and toys	Manufacture of musical instruments, sports goods, games, and toys
Fossil and nuclear fuels	Manufacture of refined petroleum products	Manufacture of refined petroleum products	Manufacture of refined petroleum products
Chemicals	Manufacture of chemicals and chemical products	Manufacture of chemicals and chemical products	Manufacture of chemicals and chemical products
	Manufacture of pharmaceuticals, medicinal chemical, and botanical products	Manufacture of pharmaceuticals, medicinal chemical, and botanical products	Manufacture of pharmaceuticals, medicinal chemical, and botanical products
	Manufacturing of chemical fiber	Manufacturing of chemical fiber	Manufacturing of chemical fiber
	Manufacture of rubber products	Manufacture of rubber products	Manufacture of rubber products
	Manufacture of plastics products	Manufacture of plastics products	Manufacture of plastics products
Non-metallic mineral	Manufacture of other non-metallic mineral products	Manufacture of other non-metallic mineral products	Manufacture of other non-metallic mineral products
Metal processing	Manufacture and casting of basic iron and steel	Manufacture and casting of basic iron and steel	Manufacture and casting of basic iron and steel
	Manufacture and casting of basic precious and other non-ferrous metals	Manufacture and casting of basic precious and other non-ferrous metals	Manufacture and casting of basic precious and other non-ferrous metals
Metal products	Manufacture of fabricated metal products, except machinery and equipment	Manufacture of fabricated metal products, except machinery and equipment	Manufacture of fabricated metal products, except machinery and equipment
Machinery	Manufacture of machinery and equipment	Manufacture of general-purpose machinery	Manufacture of general-purpose machinery
		Manufacture of special-purpose machinery	Manufacture of special-purpose machinery
Transport equipment	Manufacture of motor vehicles, trailers, semi-trailers, and other transport equipment	Manufacture of motor vehicles, trailers, semi-trailers, and other transport equipment	Manufacture of motor vehicles, trailers, semi-trailers, and other transport equipment

Table B.2 (*continued*)

Sector	1991–1992	1993–1995	1996–2002
Electrical machinery	Manufacture of electrical equipment	Manufacture of electrical equipment	Manufacture of electrical equipment
Electronic equipment	Manufacture of computer, electronic, and optical products	Manufacture of computer, electronic, and optical products	Manufacture of computer, electronic, and optical products
Measuring instruments	Manufacture of measuring, testing, navigating, and control equipment, and watches and clocks	Manufacture of measuring, testing, navigating and control equipment, and watches and clocks	Manufacture of measuring, testing, navigating and control equipment, and watches and clocks
Other manufacture	Manufacture of jewelry, bijouterie, and related articles Manufacture of prepared animal feeds Wood and bamboo harvesting	Wood and bamboo harvesting Other manufacturing	Wood and bamboo harvesting
Electricity, heat, and gas	Electricity, gas, and steam supply Manufacture of coke oven products	Electricity, gas, and steam supply Manufacture of coke oven products	Electricity, gas, and steam supply Manufacture of coke oven products
Water	Production and supply of water	Production and supply of water	Production and supply of water
Construction	Construction	Construction	Construction
Transport, storage, and post	Transport	Transport	Transport, storage, and post
Retail, hotel, and catering	Commerce	Commerce	Wholesale and retail trades Hotels and catering services
Other services	Others	Others	Financial intermediation Real estate Others

2003, 2005–2007	2010	2012	2015
Agriculture, forestry, animal husbandry, and fishery	Agriculture, forestry, animal husbandry, and fishery	Agriculture, forestry, animal husbandry, and fishery	Agriculture, forestry, animal husbandry, and fishery
Mining of coal and lignite	Mining of coal and lignite	Mining of coal and lignite	Mining of coal and lignite
Extraction of crude petroleum and natural gas	Extraction of crude petroleum and natural gas	Extraction of crude petroleum and natural gas	Extraction of crude petroleum and natural gas
Mining of ferrous metal ores Mining of nonferrous metals ores	Mining of metal ores	Mining of metal ores	Mining of metal ores
Mining of nonmetal ores Mining of other ores	Mining of nonmetal ores and other ores	Mining of nonmetal ores and other ores	Mining of nonmetal ores and other ores
Processing of food products Manufacture of food products Manufacture of beverages Manufacture of tobacco products	Manufacture of food products, beverages, and tobacco products	Manufacture of food products, beverages, and tobacco products	Manufacture of food products, beverages, and tobacco products
Manufacture of textiles	Manufacture of textiles	Manufacture of textiles	Manufacture of textiles
Manufacture of wearing apparel Manufacture of leather and related products	Manufacture of wearing apparel, leather, and related products	Manufacture of wearing apparel, leather, and related products	Manufacture of wearing apparel, leather, and related products
Manufacture of wood and of products of wood and cork, articles of straw, and plaiting materials Manufacture of furniture	Manufacture of wood and of products of wood and cork, and furniture	Manufacture of wood and of products of wood and cork, and furniture	Manufacture of wood and of products of wood and cork, and furniture
Manufacture of paper and paper products Printing and reproduction of recorded media Manufacture of musical instruments, sports goods, games, and toys	Manufacture of paper and paper products, recorded media, musical instruments, sports goods, games, and toys	Manufacture of paper and paper products, recorded media, musical instruments, sports goods, games, and toys	Manufacture of paper and paper products, recorded media, musical instruments, sports goods, games, and toys
Manufacture of refined petroleum products	Manufacture of refined petroleum products	Manufacture of refined petroleum products	Manufacture of refined petroleum products
Manufacture of chemicals and chemical products Manufacture of pharmaceuticals, medicinal chemical and botanical products Manufacturing of chemical fiber Manufacture of rubber products Manufacture of plastics products	Manufacture of chemicals and chemical products, pharmaceuticals, medicinal chemical and botanical products, chemical fiber, rubber products, and plastics products	Manufacture of chemicals and chemical products, pharmaceuticals, medicinal chemical and botanical products, chemical fiber, rubber products, and plastics products	Manufacture of chemicals and chemical products, pharmaceuticals, medicinal chemical and botanical products, chemical fiber, rubber products, and plastics products
Manufacture of other non-metallic mineral products	Manufacture of other non-metallic mineral products	Manufacture of other non-metallic mineral products	Manufacture of other non-metallic mineral products
Manufacture and casting of basic iron and steel Manufacture and casting of basic precious and other non-ferrous metals	Manufacture and casting of basic iron and steel, and basic precious and other non-ferrous metals	Manufacture and casting of basic iron and steel, and basic precious and other non-ferrous metals	Manufacture and casting of basic iron and steel, and basic precious and other non-ferrous metals
Manufacture of fabricated metal products, except machinery and equipment	Manufacture of fabricated metal products, except machinery and equipment	Manufacture of fabricated metal products, except machinery and equipment	Manufacture of fabricated metal products, except machinery and equipment
Manufacture of general-purpose machinery Manufacture of special-purpose machinery	Manufacture of general-purpose and special-purpose machinery	Manufacture of general-purpose machinery Manufacture of special-purpose machinery	Manufacture of general-purpose machinery Manufacture of special-purpose machinery

(*continued on next page*)

Table B.2 (*continued*)

Sector	1991–1992	1993–1995	1996–2002
Manufacture of motor vehicles, trailers, semi-trailers, and other transport equipment	Manufacture of motor vehicles, trailers, semi-trailers, and other transport equipment	Manufacture of motor vehicles, trailers, semi-trailers, and other transport equipment	Manufacture of motor vehicles, trailers, semi-trailers, and other transport equipment
Manufacture of electrical equipment	Manufacture of electrical equipment	Manufacture of electrical equipment	Manufacture of electrical equipment
Manufacture of computer, electronic, and optical products	Manufacture of computer, electronic, and optical products	Manufacture of computer, electronic, and optical products	Manufacture of computer, electronic, and optical products
Manufacture of measuring, testing, navigating and control equipment, and watches and clocks	Manufacture of measuring, testing, navigating and control equipment, and watches and clocks	Manufacture of measuring, testing, navigating and control equipment, and watches and clocks	Manufacture of measuring, testing, navigating and control equipment, and watches and clocks
Manufacture of jewelry, bijouterie, and related articles	Manufacture of jewelry, bijouterie, and related articles	Other manufacturing	Other manufacturing
Processing of waste resources		Processing of waste resources	Processing of waste resources
Electricity, gas, and steam supply	Electricity, gas, and steam supply	Electricity, gas, and steam supply	Electricity, gas, and steam supply
Manufacture of coke oven products	Manufacture of coke oven products	Manufacture of coke oven products	Manufacture of coke oven products
Production and supply of water	Production and supply of water	Production and supply of water	Production and supply of water
Construction	Construction	Construction	Construction
Transport, storage, and post	Transport, storage, and post	Transport, storage, and post	Transport, storage, and post
Wholesale and retail trades	Wholesale and retail trades	Wholesale and retail trades	Wholesale and retail trades
Hotels and catering services	Hotels and catering services	Hotels and catering services	Hotels and catering services
Financial intermediation	Financial intermediation	Financial intermediation	Financial intermediation
Real estate	Real estate	Real estate	Real estate
Others	Others	Others	Others

Table B.3
Splitting of sectors.

Sectors before splitting (2012/2015)	Output value	Sectors after splitting (2012/2015)	Output value
Manufacture of metal products	A	Manufacture of metal products	G*A/(A + B + C + D + E + F)+A
Manufacture of general-purpose machinery	B	Manufacture of general-purpose machinery	G*B/(A + B + C + D + E + F)+B
Manufacture of special-purpose machinery		Manufacture of special-purpose machinery	
Manufacture of motor vehicles, trailers, semi-trailers and other transport equipment	C	Manufacture of motor vehicles, trailers, semi-trailers and other transport equipment	G*C/(A + B + C + D + E + F)+C
Manufacture of electrical equipment	D	Manufacture of electrical equipment	G*D/(A + B + C + D + E + F)+D
Manufacture of computer, electronic and optical products	E	Manufacture of computer, electronic and optical products	G*E/(A + B + C + D + E + F)+E
Manufacture of measuring, testing, navigating and control equipment; watches and clocks	F	Manufacture of measuring, testing, navigating and control equipment; watches and clocks	G*F/(A + B + C + D + E + F)+F
Repairing of Metal Products, Machinery and Equipment	G	–	–

Note: There is one process of sectoral splitting in this study. Prior to 2012, there was no sector called Repairing of Metal Products, Machinery, and Equipment or its data, which means that it is necessary to split the output value of Repairing of Metal Products, Machinery, and Equipment in 2012 and 2015 into other sectors to make the statistical caliber consistent. According to China's Industrial Classification for National Economic Activities 2017, Repairing of Metal Products, Machinery, and Equipment consists of the repairing of: (1) metal products, (2) general-purpose machinery, and special-purpose machinery, (3) transport equipment, (4) electrical equipment, (5) computer, electronic, and optical products, (6) measuring, testing, navigating, and control equipment, and watches and clocks. Before 2012, these subsectors (1)–(6) were classified into (7) Manufacture of metal products, Manufacture of metal products, (8) Manufacture of general-purpose machinery and Manufacture of special-purpose machinery, (9) Manufacture of motor vehicles, trailers, semi-trailers, and other transport equipment, (10) Manufacture of electrical equipment, (11) Manufacture of computer, electronic, and optical products, (12) Manufacture of measuring, testing, navigating, and control equipment, and watches and clocks. So, this paper uses the output value of sectors (7)–(12) as a splitting ratio to split Repairing of Metal Products, Machinery, and Equipment. Table B.3 in Appendix B shows the splitting process.

Table B.4
Emission factors used in this study.

Energy			IPUU		AFOLU		
Stationary and mobile combustion	Raw coal	96,920.00 kg CO_2/TJ	Cement	0.52 Mg CO_2/Mg	Urea fertilization	Urea	0.73 kg CO_2/kg
	Cleaned coal	96,920.00 kg CO_2/TJ	Glass	0.20 Mg CO_2/Mg		Ammonium bicarbonate	0.56 kg CO_2/kg
	Other washed coal	96,920.00 kg CO_2/TJ	Nitric acid	8.00 kg N_2O/Mg	Rice cultivation		1.30 kg CH_4/hectare/day
	Coke	107,000.00 kg CO_2/TJ	Magnesium	3.98 Mg CO_2/Mg	Enteric fermentation	Dairy cattle	61.00 kg CH_4/head/year
	Coke oven gas	44,499.00 kg CO_2/TJ				Other cattle	47.00 kg CH_4/head/year
	Blast furnace gas	260,000.00 kg CO_2/TJ				Horse	18.00 kg CH_4/head/year
	Oxygen steel furnace gas	82,000.00 kg CO_2/TJ				Donkey	10.00 kg CH_4/head/year
	Other gas	128,833.00 kg CO_2/TJ				Mule	10.00 kg CH_4/head/year
	Coal tar	80,700.00 kg CO_2/TJ				Camel	46.00 kg CH_4/head/year
	Crude oil	73,300.00 kg CO_2/TJ				Hog	1.00 kg CH_4/head/year
	Gasoline	74,100.00 kg CO_2/TJ				Goat	5.00 kg CH_4/head/year
	Kerosene	71,900.00 kg CO_2/TJ				Sheep	5.00 kg CH_4/head/year
	Diesel oil	74,100.00 kg CO_2/TJ			Manure management	Dairy cattle	10.95 kg CH_4/head/year
	Fuel oil	77,400.00 kg CO_2/TJ				Other cattle	1.00 kg CH_4/head/year

Table B.4 (*continued*)

Energy			IPUU	AFOLU		
	Naphtha	74,100.00 kg CO_2/TJ			Horse	1.61 kg CH_4/head/year
	Lubricants	73,300.00 kg CO_2/TJ			Donkey	0.75 kg CH_4/head/year
	Paraffin waxes	73,300.00 kg CO_2/TJ			Mule	0.91 kg CH_4/head/year
	White spirit and SBP	73,300.00 kg CO_2/TJ			Camel	1.28 kg CH_4/head/year
	Bitumen	80,700.00 kg CO_2/TJ			Hog	3.05 kg CH_4/head/year
	Petroleum coke	97,500.00 kg CO_2/TJ			Goat	0.17 kg CH_4/head/year
	Liquefied petroleum gas	63,100.00 kg CO_2/TJ			Sheep	0.12 kg CH_4/head/year
	Refinery gas	57,600.00 kg CO_2/TJ			Poultry	0.02 kg CH_4/head/year
	Other petroleum products	73,300.00 kg CO_2/TJ			Pit storage	2.00 g N_2O-N/kg N
	Natural gas	56,100.00 kg CO_2/TJ			Liquid/slurry	2.50 g N_2O-N/kg N
	Natural gas liquids	64,200.00 kg CO_2/TJ			Solid storage	5.00 g N_2O-N/kg N
	Heat	96,920.00 kg CO_2/TJ			Dry lot	0.02 kg N_2O-N/kg N
	Electricity	96,920.00 kg CO_2/TJ			Daily spread	0.00 kg N_2O-N/kg N
	Other energy	96,920.00 kg CO_2/TJ			Anaerobic digester	0.00 kg N_2O-N/kg N
Fugitive emission	Raw coal	20.50 m^3 CO_2/Mg			Burned for fuel	0.15 g N_2O-N/kg N
	Crude oil	12.03 Gg CO_2/m^3			Others	0.00 kg N_2O-N/kg N
		3.68 Gg CH_4/m^3			Indirect volatilization	0.01 kg N_2O-N/kg N
		540.00 kg N_2O/m^3		Managed soil	Mineral fertilizers, organic amendments, and crop residues	0.01 kg N_2O-N/kg N
	Natural gas	11,318.00 Gg CO_2/m^3			Flooded rice fields	3.00 kg N_2O-N/kg N
		2,640.00 Gg CH_4/m^3			Temperate organic crop	8.00 kg N_2O-N/kg N
		0.05 Gg N_2O/m^3			Tropical organic crop and grassland soils	16.00 kg N_2O-N/kg N
					Cattle, poultry, and pigs	0.02 kg N_2O-N/kg N
					Sheep and other animals	0.01 kg N_2O-N/kg N
					Atmospheric deposition of N on soils and water surface	0.01 kg N_2O-N/kg N
					Leaching and runoff	7.50 g N_2O-N/kg N

Source: IPCC (2006).

Table B.5
Direct GHG emissions of China's 27 sectors and residential sector during 1991–2016 ($MtCO_2eq$).

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Agriculture	737.85	745.17	760.91	798.66	853.87	900.07	851.02	863.36	874.45	815.05	839.87	858.62
Coal mining	62.11	64.59	63.67	72.93	77.10	82.24	77.42	83.19	75.24	79.07	84.43	87.09
Petroleum and gas extraction	25.41	27.68	37.28	41.12	40.51	37.19	51.31	45.48	48.04	53.37	56.12	58.11
Metal ores	11.56	11.71	12.62	13.14	13.33	15.85	13.23	12.30	10.37	12.39	12.76	14.36
Nonmetal ores	15.61	16.96	14.95	17.37	18.01	19.53	17.93	16.92	14.79	17.72	18.28	18.44
Foods	85.40	89.04	94.28	95.42	104.18	103.01	92.41	90.62	86.17	86.64	90.55	93.60
Textile	65.94	69.39	63.43	69.05	73.97	66.46	60.01	53.86	48.60	52.45	55.92	59.59
Leather	6.90	7.59	8.95	9.55	9.85	9.54	8.43	9.90	9.30	10.10	10.55	11.20
Wood products	8.57	9.60	10.27	10.50	11.98	11.34	10.65	9.95	9.22	9.91	10.60	10.75
Paper and printing	42.61	45.57	49.90	49.74	54.78	54.09	48.48	47.14	42.18	50.21	53.70	58.60
Fossil and nuclear fuels	31.46	34.95	39.69	42.39	82.73	53.49	121.93	134.54	129.34	132.60	134.80	143.78
Chemicals	359.73	372.53	371.06	420.81	435.34	514.26	407.87	378.82	345.76	349.67	360.31	403.41
Non-metallic mineral	382.58	417.36	448.67	500.22	552.96	572.00	567.77	557.90	559.95	533.18	583.29	617.69
Metal processing	324.88	356.63	406.48	439.01	547.62	537.92	548.20	547.88	533.75	628.22	694.50	743.98
Metal products	17.81	18.55	18.82	19.17	21.14	22.55	19.78	20.20	19.40	20.22	22.07	24.69
Machinery	57.56	62.26	59.09	63.19	65.41	64.91	56.42	49.21	43.40	42.49	43.90	46.11
Transport equipment	23.41	24.87	24.55	22.65	26.26	27.07	26.52	25.06	24.72	25.84	27.26	30.39
Electrical machinery	11.03	11.73	11.48	12.77	12.83	12.86	12.25	11.19	10.53	10.88	10.55	11.88
Electronic equipment	7.68	8.05	7.82	7.11	5.83	5.81	7.40	7.00	7.72	8.50	8.92	10.52
Measuring instruments	2.75	2.93	2.89	2.47	2.72	2.58	2.16	2.22	2.38	2.35	2.35	2.61
Other manufacture	38.29	34.58	52.06	37.50	29.09	26.00	25.40	20.05	19.38	20.65	19.69	19.55
Electricity, heat, and gas	23.99	32.34	49.55	44.09	48.37	95.44	127.11	119.51	121.66	118.74	123.57	131.53
Water	2.91	3.23	3.41	3.78	4.24	4.14	4.45	4.65	5.52	5.45	5.30	5.10
Construction	26.81	29.25	25.47	25.57	24.40	25.65	22.88	31.06	29.04	46.08	48.16	51.94
Transport, storage, and post	112.83	116.54	120.65	118.45	126.19	125.21	159.37	174.69	197.65	237.42	244.21	265.91
Retail, hotel, and catering	30.54	32.41	41.87	39.02	42.02	46.42	44.91	48.49	53.02	61.39	66.33	73.71
Other services	88.50	94.61	116.06	118.36	101.96	113.44	86.51	89.58	94.74	112.43	117.09	126.20
Residential sector	435.88	404.07	396.05	370.52	395.00	401.77	366.06	290.37	291.40	323.59	329.51	343.27

2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
879.75	926.92	956.59	853.37	864.48	871.14	886.76	893.34	902.01	914.03	931.95	944.22	958.34	943.35
105.73	86.19	94.52	106.29	119.52	125.16	189.15	199.55	211.85	219.94	234.14	184.88	145.52	107.18
59.65	49.98	50.34	53.32	55.78	57.77	55.98	58.82	55.88	54.59	58.26	59.33	58.30	52.11
18.42	25.90	30.39	34.27	37.11	40.27	38.13	60.44	54.33	52.45	57.51	55.16	44.89	37.87
20.94	18.34	19.52	23.41	25.26	26.49	28.44	28.36	28.68	36.29	36.49	35.96	31.18	27.40
88.02	126.53	143.14	154.87	174.52	190.64	193.52	199.54	203.11	201.94	203.18	180.40	176.96	168.72

(continued on next page)

Table B.5 (*continued*)

2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
65.39	87.46	96.88	103.17	107.98	105.91	106.18	110.29	111.46	102.33	102.75	88.71	86.39	81.08
12.09	15.87	18.03	22.77	23.97	24.06	23.49	23.87	22.50	25.91	24.82	23.13	22.07	20.61
13.32	17.37	20.74	24.75	27.68	31.07	32.80	34.14	34.52	35.17	34.33	35.67	31.12	23.32
59.96	74.39	81.72	87.09	91.02	99.77	107.53	110.73	111.21	103.43	97.85	85.47	79.44	75.19
169.00	212.06	210.40	235.10	260.41	269.91	308.77	293.86	312.35	322.30	328.42	338.57	348.98	316.96
449.31	591.57	665.46	742.37	808.29	826.58	843.49	952.61	1,050.03	1,071.82	1,120.58	1,152.13	1,211.28	1,105.69
786.06	949.55	1,059.40	1,140.72	1,250.67	1,311.20	1,405.72	1,539.75	1,715.73	1,697.27	1,740.66	1,772.51	1,663.66	1,582.80
921.51	1,066.20	1,382.36	1,578.46	1,828.48	1,936.80	2,218.60	2,486.17	2,769.97	2,862.09	3,056.04	3,124.98	2,972.01	2,954.76
25.27	26.95	30.12	38.36	42.76	45.06	44.50	48.95	47.07	55.96	61.99	58.68	55.72	56.77
50.66	57.88	70.05	81.65	90.79	99.91	102.31	110.57	129.34	95.85	91.28	90.52	84.97	83.00
27.88	30.90	32.34	37.37	40.44	44.59	46.77	55.24	57.71	57.35	58.77	53.98	51.12	48.55
13.43	18.67	20.46	25.65	26.59	28.72	28.54	31.84	32.44	31.29	32.49	29.71	28.46	27.43
12.51	14.41	16.36	21.37	23.55	24.30	24.53	27.63	27.53	26.90	27.88	28.57	29.80	31.50
3.25	2.51	2.96	3.51	3.87	3.77	3.95	4.56	4.06	3.90	4.00	3.66	3.45	3.29
19.06	11.12	12.88	14.13	14.57	16.14	16.05	18.12	19.56	17.87	18.04	18.54	18.77	18.76
151.96	112.89	122.12	123.01	132.51	143.72	148.76	169.41	190.14	176.95	175.37	152.33	152.04	159.84
5.25	5.96	6.35	6.95	7.27	7.57	8.00	9.12	9.85	10.38	10.71	10.84	11.20	11.66
57.67	65.57	70.73	77.74	83.64	75.18	93.56	113.27	121.24	126.20	140.63	151.01	155.23	159.86
308.33	363.90	393.48	429.52	460.09	489.90	497.97	551.77	601.93	660.39	703.90	732.72	769.75	789.66
87.17	100.06	108.15	116.11	124.56	126.88	136.27	141.65	162.98	174.79	187.54	184.93	192.12	194.58
146.54	165.69	177.75	192.48	207.10	223.21	233.92	251.23	278.67	300.55	326.73	320.92	348.05	352.03
379.66	424.89	450.50	486.76	522.33	528.56	550.59	583.32	627.44	656.67	702.38	723.57	765.38	813.36

Table B.6
27 sectors' total GHG emissions during 1991–2016 ($MtCO_2eq$).

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Agriculture	1,119.77	1,154.75	1,218.30	1,285.51	1,434.08	1,437.97	1,463.19	1,374.08	1,406.27	1,335.35	1,375.90	1,510.42
Coal mining	143.61	163.90	141.02	149.99	171.50	167.57	242.16	205.76	204.66	230.55	234.98	380.08
Petroleum and gas extraction	40.40	46.80	57.01	68.53	64.85	56.21	72.41	60.19	63.11	66.90	74.27	97.90
Metal ores	29.19	36.58	35.05	45.07	64.10	60.40	82.37	57.61	46.69	53.53	52.48	88.01
Nonmetal ores	71.99	135.42	69.36	102.41	249.93	119.24	177.88	131.21	107.77	128.65	125.66	205.85
Foods	335.62	409.82	352.38	377.68	666.96	471.74	507.04	415.72	371.74	353.67	344.96	362.91
Textile	346.58	481.00	316.50	366.24	656.61	426.43	498.62	319.09	269.70	272.17	276.80	342.01
Leather	36.97	54.79	46.69	60.23	102.13	58.02	68.00	50.86	47.91	49.62	48.24	61.67
Wood products	44.96	73.35	47.48	59.69	125.08	68.05	92.20	80.42	75.59	79.48	79.25	120.19
Paper and printing	185.46	268.28	290.46	325.36	532.98	281.83	325.95	222.50	200.13	241.47	246.57	391.60
Fossil and nuclear fuels	99.09	127.28	123.83	173.19	354.54	215.36	627.04	719.21	729.69	779.42	734.49	871.44
Chemicals	1,352.17	1,770.28	1,613.27	2,080.78	2,966.08	2,424.35	2,608.45	1,876.39	1,646.27	1,613.79	1,618.21	2,239.70
Non-metallic mineral	1,525.89	2,153.16	1,521.60	1,951.91	3,822.55	2,810.13	4,518.20	3,025.22	2,701.49	2,324.22	2,263.47	2,626.35
Metal processing	1,225.45	1,558.28	1,277.51	1,679.32	3,236.57	2,567.91	3,188.75	2,667.91	2,594.57	2,989.61	3,192.42	4,713.52
Metal products	86.83	141.22	90.71	103.93	192.41	143.52	190.81	139.01	128.17	128.59	126.59	176.05
Machinery	222.57	356.89	264.41	301.57	478.21	321.74	376.66	241.35	217.85	216.97	220.22	309.73
Transport equipment	80.32	100.44	81.93	88.00	132.10	111.06	140.11	99.27	99.40	108.45	108.29	134.66
Electrical machinery	43.99	62.69	46.59	62.61	84.65	66.51	83.09	52.95	46.44	44.18	40.98	53.41
Electronic equipment	29.70	40.55	33.90	33.42	34.57	28.72	40.15	29.11	33.11	35.59	39.68	54.16
Measuring instruments	8.67	10.02	6.79	6.30	7.95	9.15	12.07	8.96	10.38	10.56	10.91	16.42
Other manufacture	0.00	0.00	193.48	100.73	65.91	85.84	241.52	110.54	99.01	99.90	87.41	145.12
Electricity, heat, and gas	56.98	89.26	130.18	111.71	125.37	223.35	314.20	242.64	240.37	245.75	250.76	338.15
Water	0.00	0.00	3.41	3.78	0.00	7.25	15.06	10.83	12.23	12.49	12.19	16.91
Construction	88.99	107.35	80.23	80.83	87.57	74.60	85.95	93.05	92.71	158.31	171.76	225.42
Transport, storage, and post	186.79	183.95	201.77	183.72	204.96	206.89	269.85	294.96	343.29	425.09	444.44	518.26
Retail, hotel, and catering	57.51	68.83	89.70	75.08	77.31	84.55	75.70	85.80	94.53	111.61	120.72	140.76
Other services	140.66	150.72	195.34	187.32	130.70	180.26	120.58	143.92	154.20	186.01	193.50	224.01

2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
1,527.14	1,505.34	1,726.44	1,476.13	1,521.05	1,496.07	1,528.86	1,573.22	1,586.66	1,598.86	1,607.81	1,622.87	1,685.71	1,661.69
335.71	222.42	259.33	250.60	245.47	253.22	393.79	434.37	441.87	441.60	511.35	472.88	456.88	326.76
89.45	70.48	63.13	79.13	82.45	97.32	92.78	98.75	93.02	88.09	105.48	101.08	107.77	55.25
78.83	90.02	113.23	111.50	119.99	115.85	116.39	174.44	144.14	133.11	175.43	170.57	166.22	132.60
145.56	106.95	160.39	141.50	186.92	93.12	102.32	83.97	75.11	81.69	98.03	102.60	102.36	98.50
317.30	439.92	518.85	566.70	645.04	830.58	883.93	946.71	907.92	855.95	868.27	782.74	778.46	751.08
314.34	474.69	474.18	497.36	553.71	554.52	544.40	535.32	577.84	534.11	563.97	481.04	482.35	443.56
55.94	74.97	93.21	105.48	115.64	124.52	122.22	124.48	111.17	121.07	105.49	98.52	87.50	82.59
100.14	109.61	139.45	145.98	181.49	171.28	184.34	177.64	164.26	154.06	152.80	162.42	142.48	107.41
290.83	345.25	445.84	408.16	454.65	483.21	530.45	537.93	488.95	433.16	442.45	393.27	383.16	363.09
931.68	1,248.11	1,339.94	1,799.54	1,772.04	1,551.84	1,802.44	1,480.94	1,640.76	1,721.85	1,695.00	1,714.12	1,632.86	1,349.56
2,034.27	1,762.88	2,309.80	3,624.95	3,703.08	4,153.72	4,348.01	4,920.09	5,401.49	5,535.15	6,029.10	6,393.00	6,841.68	6,174.37
2,995.18	9,337.39	10,062.87	5,364.89	5,881.53	5,607.10	6,434.73	7,015.33	7,128.76	6,703.17	7,999.76	8,059.05	8,185.25	7,857.05
4,120.07	4,375.69	5,638.48	6,920.86	8,284.39	10,314.45	11,746.71	13,958.09	15,056.39	15,784.95	19,478.54	19,655.57	21,650.87	19,934.43
154.24	154.98	189.14	217.87	251.52	252.53	251.75	261.86	236.99	281.44	312.36	304.82	287.88	295.10
261.28	260.84	378.19	388.38	438.54	461.43	497.68	522.82	608.24	448.14	434.44	428.32	402.17	392.09
108.23	115.53	148.39	182.61	191.23	222.26	247.22	289.17	297.29	288.15	286.53	265.98	244.55	232.96

Table B.6 (*continued*)

2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
57.09	75.22	94.87	120.97	119.26	157.68	165.64	200.12	200.70	187.28	181.13	168.30	152.31	146.55
58.69	67.99	80.19	111.93	122.39	152.47	154.82	179.68	172.81	157.61	157.30	161.68	162.80	171.54
14.05	11.28	14.50	15.14	16.25	17.80	18.95	21.75	19.57	17.17	16.86	15.82	14.31	13.50
104.56	56.92	101.39	80.88	142.37	45.97	45.95	40.82	42.47	57.31	48.27	54.08	91.24	84.92
576.73	316.68	400.44	426.84	472.78	559.64	576.83	681.25	775.80	688.42	829.97	649.67	685.52	773.52
15.13	17.00	23.43	18.92	23.41	18.54	20.06	20.63	22.15	22.38	26.20	27.85	31.04	35.55
222.95	274.18	289.45	306.80	341.82	302.01	348.24	425.27	448.44	474.01	566.91	619.15	672.20	707.17
650.27	764.38	926.20	995.35	1,021.64	1,140.00	1,231.96	1,447.24	1,410.11	1,713.48	1,895.45	1,959.74	2,055.56	2,140.74
166.66	186.18	203.00	216.83	205.28	217.53	226.75	210.10	262.55	280.18	310.99	310.08	331.31	342.60
256.86	317.00	326.42	345.70	322.36	383.29	392.65	403.88	496.22	539.17	604.11	592.50	622.57	630.49

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