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Non-CO_2 Greenhouse Gas Emissions in China 2012: Inventory and Supply Chain Analysis

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Key Points:
- Both production- and consumption-based non-CO_2 GHG emissions in China 2012 are examined
- Four fifths of the emissions (2003.0 Mt. CO_2-eq) are driven by urban consumption (30.1%), capital formation (28.2%), and exports (20.6%)
- Key emission sectors and critical embodied emission paths in supply chains are addressed for mitigating non-CO_2 GHG emissions

Supporting Information:
- Supporting Information S1.

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Abstract Reliable inventory information is critical in informing emission mitigation efforts. Using the latest officially released emission data, which is production based, we take a consumption perspective to estimate the non-CO_2 greenhouse gas (GHG) emissions for China in 2012. The non-CO_2 GHG emissions, which cover CH_4, N_2O, HFCs, PFCs, and SF_6, amounted to 2003.0 Mt. CO_2-eq (including 1871.9 Mt. CO_2-eq from economic activities), much larger than the total CO_2 emissions in some developed countries. Urban consumption (30.1%), capital formation (28.2%), and exports (20.6%) derived approximately four fifths of the total embodied emissions in final demand. Furthermore, the results from structural path analysis help identify critical embodied emission paths and key economic sectors in supply chains for mitigating non-CO_2 GHG emissions in Chinese economic systems. The top 20 paths were responsible for half of the national total embodied emissions. Several industrial sectors such as *Construction, Production and Supply of Electricity and Steam*, *Manufacture of Food and Tobacco* and *Manufacture of Chemicals, and Chemical Products* played as the important transmission channels. Examining both production- and consumption-based non-CO_2 GHG emissions will enrich our understanding of the influences of industrial positions, final consumption demands, and trades on national non-CO_2 GHG emissions by considering the comprehensive abatement potentials in the supply chains.

1. Introduction

Carbon dioxide (CO_2) emission mitigation has attracted increasing attention around the world, responding to the Paris Agreement to hold the global average temperature increase well below 2°C. However, insufficient attention has been given to non-CO_2 greenhouse gases (GHGs), which have greater short-term impacts than CO_2 and also contribute significantly to climate change (Montzka et al., 2011). China is the largest contributor to world's CO_2 emissions, as well as a main non-CO_2 GHG emitter (World Bank, 2017). Chinese governments have attached great importance to climate change, making climate action as a strategic task in the economic and social development. The country's nationally determined contribution to the Paris Agreement on climate change includes a pledge to peak its CO_2 emissions by around 2030, but its non-CO_2 GHG emissions could nearly double by 2030 (relative to 2005 levels) under the existing policy framework (Yao et al., 2016). The rapid increases of non-CO_2 GHG emissions are posing a severe challenge to China's policies and actions for addressing climate change.

Reliable GHG emission inventory serves as the basis for tracking reduction progress and designing climate policies. The major non-CO_2 GHG emissions include CH_4, N_2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The various kinds of gases and different emission sources make it difficult to build non-CO_2 GHG emission inventories. Most existing non-CO_2 GHG emission inventories of China only identified some typical emission sources such as livestock, rice cultivation, energy activities, industrial processes, and waste management (e.g., Chen et al., 2017a; Du et al., 2017; Fang et al., 2016; Peng et al., 2016; Wang et al., 2017a; Yang et al., 2014; Zhang & Chen, 2014; Zhang et al., 2014a). Moreover, there are great discrepancies between emission estimates from international institutions (e.g., European Commission, Joint Research Centre (JRC)/ PBL Netherlands Environmental Assessment Agency, 2014; United States Environmental Protection Agency, 2012) and China's national reports. In 2017, China reported an up-to-date national GHG inventory in its first Biennial Update Report (BUR) on Climate Change submitted to the UNFCCC (Climate Change Department of National Development and Reform Commission (CCDNDRC), 2017). This latest officially released inventory reported all major non-CO_2 GHG emissions in 2012, with the updated activity data, methodologies, and emission factors (CCDNDRC, 2017). The inventory is referred to as production-based emission inventory.

One limitation of the production-based inventory is that it cannot present a full picture of the production chain. As a supplementary, environmental extended input–output analysis (EEIOA) can help estimate the specific contribution of consumption to regional emissions. It can shed light on resource uses and environmental emissions by capturing the economic relationships among industrial sectors (Huo et al., 2014; Liu & Liang, 2017; Meng et al., 2016, 2017; Miller & Blair, 2009; Tang et al., 2018; Wu & Chen, 2017). A series of studies have used the method to understand GHGs emission from a consumption perspective at different scales, such as CO_2 emissions in China (e.g., Chen et al., 2017b; Chen & Chen, 2010; Dong et al., 2018; Feng & Hubacek, 2016; Hawkins et al., 2015; Peters, 2008; Yuan et al., 2017; Zhang et al., 2014a, 2017b). Particularly, Zhang and his colleagues (Chen & Zhang, 2010; Zhang et al., 2011, 2014b, 2015, 2016; Zhang & Chen, 2010) have contributed a lot to non-CO_2 GHGs (such as CH_4) mitigation in China by providing insights into demand-driven emissions. However, there is still a gap in understanding all non-CO_2 GHGs from a consumption perspective with the authorized official inventory.

Structural path analysis (SPA) enables to examine how final demand purchase initiates production processes, following the production network from final demand through the domestic production processes (Zhang et al., 2017a). SPA has been used to analyze flows of energy, carbon, water, and other physical quantities through industrial networks, and help design policies from consumption perspective (e.g., Davis et al., 2011; Lenzen, 2016; Meng et al., 2015; Skelton et al., 2011; Wang et al., 2017b; Yang et al., 2015; Yuko, 2012). Nevertheless, the dominant paths that drive non-CO_2 GHG emissions along the supply chain have not yet fully understood.

The aim of this paper is to clarify the role of specific consumption in China's non-CO_2 GHG emissions and how the emissions are initialed through the supply chain, by using EEIOA and SPA. The non-CO_2 GHG emissions covers CH_4, N_2O, HFCs, PFCs, and SF_6, based on the latest officially released national inventory. Examining both production- and consumption-based non-CO_2 GHG emissions will be useful for understanding and identifying the influence of industrial positions, final consumption demands, and trades on national non-CO_2 GHG emissions. Key emission sectors and embodied emission paths in supply chains, and related comprehensive abatement potentials in Chinese economic systems will be addressed.

2. Methodology and Data

2.1. Input–Output Embodiment Analysis

For the national input–output table of China, the basic row balance can be expressed as:

$$\mathbf{X} = \mathbf{AX} + \mathbf{F} - \mathbf{X}^m \tag{1}$$

where $\mathbf{X}$ is the total output, in terms of a column vector; $\mathbf{A}$ is the technology coefficients matrix to describe the relationship between all sectors of the economy, of which the element is $a_{ij} = Z_{ij}/X_j$, with Z_{ij} and X_j standing for the input from Sector i to Sector j and the total output of Sector j, respectively; $\mathbf{F}$ is the final demand column vector indicating rural and urban households consumption, government consumption, gross capital formation, export and others; and $\mathbf{X}^m$ is the import, in terms of a column vector.

Since we focus on sectoral allocation of emissions in domestic production, the import items are removed to isolate the domestic supply chain in China. Following previous studies (Meng et al., 2015; Zhang et al., 2017a), we assume that each economic sector and domestic demand category utilize sectoral imports in the same proportions. Thus, new requirement coefficient matrices in which only domestic goods are included can be derived as,

$$\mathbf{A}^d = (\mathbf{I} - \mathbf{M})\,\mathbf{A} \tag{2}$$

$$m_{ii} = \frac{X_i^m}{X_i + X_i^m - f_i^e} \quad (3)$$

where $\mathbf{A}^d$ is the direct requirement coefficient matrix of domestic production coefficients; $\mathbf{I}$ is the identity matrix; $\mathbf{M} = diag\,(m_{ii})$, and m_{ii} is the share of imports in the supply of products and services to each sector.

The new equations are as follows

$$\mathbf{X} = \mathbf{Z}^d + \mathbf{y}^d = \mathbf{Z}^d + \mathbf{f}^d + \mathbf{f}^e = \mathbf{A}^d\mathbf{X} + \mathbf{f}^d + \mathbf{f}^e \quad (4)$$

where $\mathbf{Z}^d$is the matrix of domestic intermediate demands; $\mathbf{y}^d$ is the vector of final demand excluding imports for final consumption; $\mathbf{f}^d$ is the vector of domestic final consumption; and $\mathbf{f}^e$ is the vector of domestic exports.

Rearranging equation 4 leads to following basic equations,

$$\mathbf{X} = \mathbf{Z}^d + \mathbf{y}^d = \left(\mathbf{I} - \mathbf{A}^d\right)\left(\mathbf{f}^d + \mathbf{f}^e\right) = \mathbf{L}^d\left(\mathbf{f}^d + \mathbf{f}^e\right) \quad (5)$$

where $\mathbf{I}$ is the identity matrix; and $\mathbf{L}^d = (\mathbf{I} - \mathbf{A}^d)^{-1}$ is the domestic Leontief inverse matrix, whose element l_{ij} tracks the overall direct and indirect input along the domestic supply chain from Sector i while generating unit output in Sector j.

According to equation 5, it is easy to formulate the total embodied emissions from domestic production (*EEP*) as

$$\begin{aligned} \mathbf{EEP} &= \mathbf{c}\mathbf{L}^d\left(\mathbf{f}^d + \mathbf{f}^e\right) \\ &= \mathbf{c}\left(\mathbf{I} - \mathbf{A}^d\right)^{-1}\left(\mathbf{f}^d + \mathbf{f}^e\right) \\ &= \varepsilon^d\left(\mathbf{f}^d + \mathbf{f}^e\right) \\ &= \varepsilon^d\mathbf{f}^d + \varepsilon^d\mathbf{f}^e \end{aligned} \quad (6)$$

where $\mathbf{c}$ is the direct emission intensity (i.e., the direct emission per unit of value of industrial output); ε^d is the domestic embodied (direct plus indirect) emission intensity, in terms of a row vector; $\varepsilon^d\mathbf{f}^d$ is the domestic emissions embodied in domestic final consumption; and $\varepsilon^d\mathbf{f}^e$ is the domestic emissions embodied in exports.

To perform SPA for the embodied emission paths, the revised Leontief inverse matrix in equation 5 is expanded using Taylor series,

$$\mathbf{L}^d = \left(\mathbf{I} - \mathbf{A}^d\right)^{-1} = \mathbf{I} + \mathbf{A}^d + \left(\mathbf{A}^d\right)^2 + \left(\mathbf{A}^d\right)^3 + \cdots + \left(\mathbf{A}^d\right)^t \quad (7)$$

On the right-hand side of equation 7, each element in the expansion denotes a different production layer (*PL*) or tier. We define a production layer (*PL*) as each term in the power series expansion, $PL^t = (\mathbf{A}^d)^t$. Each additional layer, $PL^{t+1} = PL^t\mathbf{A}^d$, represents the production of intermediate products in $(t+1)$th production tier used as inputs into the tth production tier. Thereafter, embodied emissions in final demands (y^d) can be calculated as,

$$\varepsilon^d\left(\mathbf{I} - \mathbf{A}^d\right)^{-1}\mathbf{y}^d = \varepsilon^d\mathbf{y}^d + \varepsilon^d\mathbf{A}^d\mathbf{y}^d + \varepsilon^d\left(\mathbf{A}^d\right)^2\mathbf{y}^d + \varepsilon^d\left(\mathbf{A}^d\right)^3\mathbf{y}^d + \cdots + \varepsilon^d\left(\mathbf{A}^d\right)^t\mathbf{y}^d \quad (8)$$

where $\varepsilon^d(\mathbf{A}^d)^t\mathbf{y}^d$ represents the contribution of embodied emissions from the tth production tier. Detailed procedures to illustrate the process of SPA can be referred to Meng et al. (2015) and Zhang et al. (2017a).

2.2. Data Sources and Preparation

To date, China has officially reported three national GHG inventories—by gas and by source. The 2012 national inventory is the latest official emission inventory covering all the non-CO_2 GHGs. To reflect China's actual emissions and reduce inventory uncertainty, emissions from key categories were estimated using the latest national statistical data and as many higher-tier methods and country-specific emission factors as possible (CCDNDRC, 2017). In this study, the relevant emission data for the non-CO_2 GHGs covering CH_4, N_2O, and F-gases (i.e., HFCs, PFCs, and SF_6) are mainly adopted from the National Greenhouse Gas Inventory

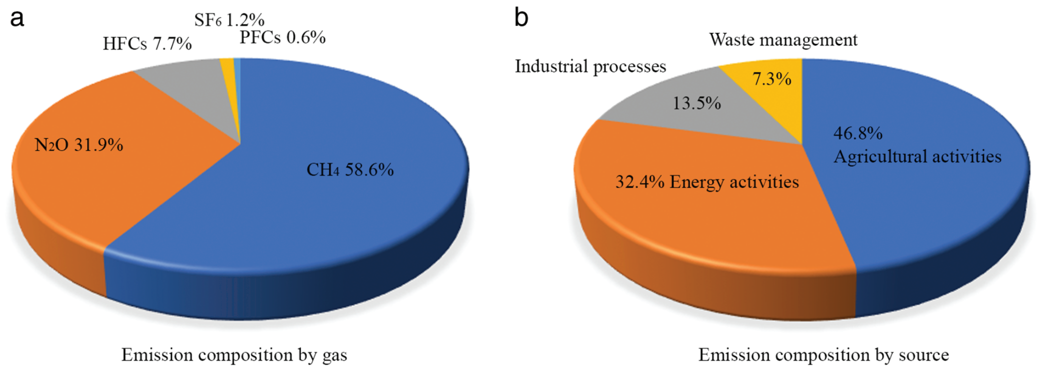

Figure 1. Composition of non-CO_2 GHG emissions in the national inventory.

Table 1.
CH_4 and N_2O Emissions in the National Inventory

Emission sources	CH_4 emissions (Mt CO_2-eq)	Fraction (%)	N_2O emissions (Mt CO_2-eq)	Fraction (%)
1. Agricultural activities	480.6	40.9	457.3	71.6
2. Energy activities	579.3	49.3	69.4	10.9
3.Industrial processes	0.1	0.0	79.1	12.4
4. Waste management	113.9	9.7	32.6	5.1
Total emissions	1173.9	100.0	638.3	100.0

of 2012, excluding land-use change and forestry (LUCF). It is noticeable that the CO_2 equivalent emissions are highly dependent on the choice of global warming potential (GWP) factor, but the GWP values provided by IPCC are very different (Intergovernmental Panel on Climate Change (IPCC), 2014), as listed in Table S1 in Supporting Information S1. Since the GWPs over a 100-year time horizon in the IPCC's Second Assessment Report (SAR) are in line with the metric adopted by the Kyoto Protocol, we directly adopt the emissions calculated by the GWP_{100} values from the AR2 to compare different GHGs relative to CO_2.

Since 1987, the Chinese government began to compile the benchmark input–output table at the national scale every 5 years. The latest input–output table for 2012 was released by the National Bureau of Statistics of China in 2015 (National Bureau of Statistics of China (NBSC), 2015a). All the 42 industrial sectors are consolidated into 26 industrial sectors to comply with relevant environmental resources data (see Table S2 in Supporting Information S1). To perform the input–output modeling, we have to extract the direct non-CO_2 GHG emission data in the national inventory that are related to economic activities. Then all the non-CO_2 GHG emissions in terms of various source categories are reallocated and disaggregated into the economic sector. It is clear that some emission sources can be referred to an industrial sector directly. For instance, the CH_4 emissions from agricultural activities, coal mining and oil and gas system leakage can be classified to corresponding industrial sectors such as *Agriculture*, *Mining and Washing of Coal* and *Extraction of Crude Petroleum and Natural Gas*. The emissions of F-gases from metal production are attributed to corresponding economic sectors such as *Manufacture of Fabricated Metal Products, Except Machinery, and Equipment*. The production of halocarbons and SF_6 are attributed to *Manufacture of Chemicals and Chemical Products*. The consumption of halocarbons and SF_6 are mainly attributed to *Manufacture of General-Purpose and Special-Purpose Machinery* and *Manufacture of Electrical Machinery and Apparatus*.

If the emission category refers to various sectors, we should calculate the sectoral emissions based on the activity-level data and the method of national inventory compilation. Some assumptions have been made as a preliminary approximation, in accordance with the total emissions from this category in the official national inventory. The calculation of sectoral CH_4 and N_2O emissions from fossil fuel combustion is based on the energy consumption data and the emission factors of various fuels associated with different

Table 2.
F-Gases Emissions and by Source (Mt CO_2-eq)

Emission sources	HFCs	PFCs	SF_6	Total	Fraction (%)
Metal products		10.9		10.9	5.7
Production of halocarbons and SF_6	117.8	0.0		117.9	61.8
Consumption of halocarbons and SF_6	36.6	1.0	24.4	62.0	32.5
Total emissions	154.4	12.0	24.4	190.8	**100.0**

Table 3.
GHG Emissions in China and Representative Countries in 2012 (Mt CO_2-eq)

Country	Non-CO_2 GHGs	CO_2	Total GHGs
Japan	249.3	1229.6	1478.9
Germany	212.4	739.3	951.7
Australia	386.2	375.5	761.7
Canada	545.5	481.6	1027.1
Russian Federation	967.8	1835.6	2803.4
United States	1228.0	5115.8	6343.8
European Union	1213.8	3488.3	4702.1
India	984.4	2018.5	3002.9
Brazil	2519.4	470.0	2989.4
China	2003.0	9893.0	11, 896.0

Sources: World Bank (2017) and CCDNDRC (2017).

processes. The energy consumption data is obtained from China Energy Statistical Yearbook 2014 (NBSC, 2015b) with the Energy Balance Sheet of China (standard quantity). The procedure of data processing for energy-related emissions is consistent with Guan et al. (2012).

In addition, sector-specific CH_4 and N_2O emissions from wastewater management in the national inventory are not available. Referring to Zhang et al. (2016), the CH_4 emissions from industrial wastewater management are reallocated into different industrial sectors on the basis of their activity data of the chemical oxygen demand removed and discharged into water bodies and corresponding emission correction factors in IPCC (2006) and Ma and Gao (2011). The allocation of emissions from municipal solid waste and domestic sewage to the detailed economic sectors follows the study of Zhang et al. (2015). One third of such emissions can be attributed to the construction and service sectors, and then the sectoral emissions can be assigned by their economic outputs. The environmental resource data required to make additional estimations for sectoral CH_4 and N_2O emissions are collected from multiple statistical yearbooks of China such as China Energy Statistical Yearbook (NBSC, 2015b), China Environmental Statistical Yearbook (CESY, 2013) and China Statistical Yearbook (CSY, 2013).

3. Production-Based Non-CO_2 GHG Emissions

3.1. Total Emission Inventories

China's non-CO_2 GHG emissions in 2012 amounted to 2003.0 Mt. CO_2-eq and comprised 16.8% of China's national GHG emissions, excluding LUCF. CH_4 was the largest contributor to non-CO_2 GHG emissions, accounting for 9.9% of the country's total GHG emissions, followed by N_2O (5.4%) and F-gases (1.6%). As to the emission composition, CH_4, N_2O, HFCs, PFCs, and SF_6 accounted for 58.6%, 31.9%, 7.7%, 0.6%, and 1.2% of the total, respectively, as shown in Figure 1a.

Agricultural activities were the main source of China's non-CO_2 GHG emissions. In 2012, the emissions from agricultural activities contributed 46.8% to the national total, which were dominated by enteric fermentation, rice cultivation and agriculture soils. The second emission source was energy activities, contributing 32.4%, mainly caused by fugitive CH_4 emissions from solid fuels. Industrial processes and waste management accounted for 13.5% and 7.3% respectively, as displayed in Figure 1b.

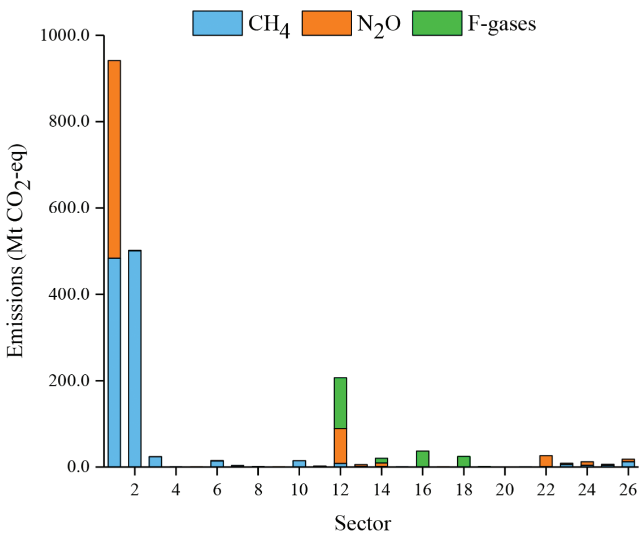

Figure 2. Non-CO_2 GHG emissions by sector.

Table 1 presents a detailed breakdown of CH_4 and N_2O emissions in 2012. China's CH_4 emissions were 1173.9 Mt. CO_2-eq, mainly contributed by energy activities, agricultural activities, and waste management. Among all energy activities, the fugitive emission from solid fuels was the main contributor, amounting to 500.8 Mt. CO_2-eq. Agricultural CH_4 emissions mainly sourced from enteric fermentation (225.6 Mt. CO_2-eq) and rice cultivation (177.6 Mt. CO_2-eq). Further details in the national inventory are presented in Table S3 in Supporting Information S1.

China's N_2O emissions in 2012 were 638.3 Mt. CO_2-eq, referring to emissions from agricultural activities, industrial processes, energy activities, and waste management. Owing to massive N_2O emissions from manure management and agriculture soils (See Table S4 in Supporting Information S1), agricultural activities were the major contributors, amounting to 457.3 Mt. CO_2-eq and 71.6% of the total. Emissions from industrial processes and energy activities reached 79.1 and 69.4 Mt. CO_2-eq, respectively. In addition, the N_2O emissions originated from waste management summed up to only 32.6 Mt. CO_2-eq.

All the main F-gases were taken into consideration in the national inventory, including HFCs (covering HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, and HFC-245fa), PFCs (i.e., CF_4 and C_2F_6) and SF_6, as listed in Table S5 in Supporting Information S1. F-gases emissions of China totaled 190.8 Mt. CO_2-eq, all of which were from industrial processes. Among various emission types, HFCs emissions had the largest amount of 154.4 Mt. CO_2-eq and accounted for 80.9% of the total. PFCs and SF_6 emissions had minor contributions with the amounts of 12.0 and 24.4 Mt. CO_2-eq, respectively. The production of halocarbons and SF_6 contributed 117.9 Mt. CO_2-eq, up to 61.8% of the total. Detailed results are listed in Table 2.

Table 3 presents the comparison of China's GHG emissions with those of the major emission countries. The amount of China's non-CO_2 GHG emissions was only second to that of Brazil, 1.6 times of those of United States and European Union. Obviously, the equivalent CO_2 emissions of China's non-CO_2 GHG emissions were much larger than the total GHG emissions in some developed countries such as Japan, Germany, Australia, and Canada, and very close to the CO_2 emissions of Russian Federation and India in the same year. In fact, only considering China's CH_4 emissions, its value amounted to 1173.9 Mt. CO_2-eq, also higher than some important emitters around the world. By using the GWP values from the IPCC's Fourth Assessment Report (AR4, see Table S1 in Supporting Information S1), China's total non-CO_2 GHG emissions could even hit a higher value of 2237.6 Mt. CO_2-eq. All the comparisons highlight the unique importance of China's non-CO_2 GHG emissions in the national and the global GHG emission inventories.

3.2. Emission Inventories by Economic Sector

Allocating the production-based emission inventory data to a concrete economic sector is essential for consumption-based accounting. The total non-CO_2 GHG emissions by Chinese economy amounted to

1871.9 Mt. CO_2-eq in 2012 (93.5% of the national total), to which CH_4 contributed 1082.4 Mt. CO_2-eq, N_2O 598.7 Mt. CO_2-eq, and F-gases 190.8 Mt. CO_2-eq.

Figure 2 further presents the sectoral distribution of non-CO_2 GHG emissions in terms of CH_4, N_2O and F-gases. The CH_4 emissions were mainly from Sectors 1 (*Farming, Forestry, Animal Production and Fishery*) and 2 (*Mining and Washing of Coal*), which accounted for 44.7% and 46.3% of the total, respectively. For the N_2O emissions, direct emissions from Sector 1 amounted to 457.6 Mt. CO_2-eq, up to76.4% of the total, followed by those of Sectors 12 (*Manufacture of Chemicals and Chemical Products*) and 22 (*Production and Supply of Electricity and Steam*), accounting for 13.4% and 4.2%, respectively. The dominant sector of F-gas emissions was Sector 12, accounting for 61.8% of the total emissions, followed by Sectors 16 (*Manufacture of General-Purpose and Special-Purpose Machinery*) for 19.2% and 18 (*Manufacture of Electrical Machinery and Apparatus*) for 12.8%. As a whole, Sectors 1 (50.3%), 2 (26.8%), and 12 (11.0%) were responsible for 88.1% of the total economy-wide non-CO_2 GHG emissions. Detailed information of direct emission inventories are listed in Table S6 in Supporting Information S1.

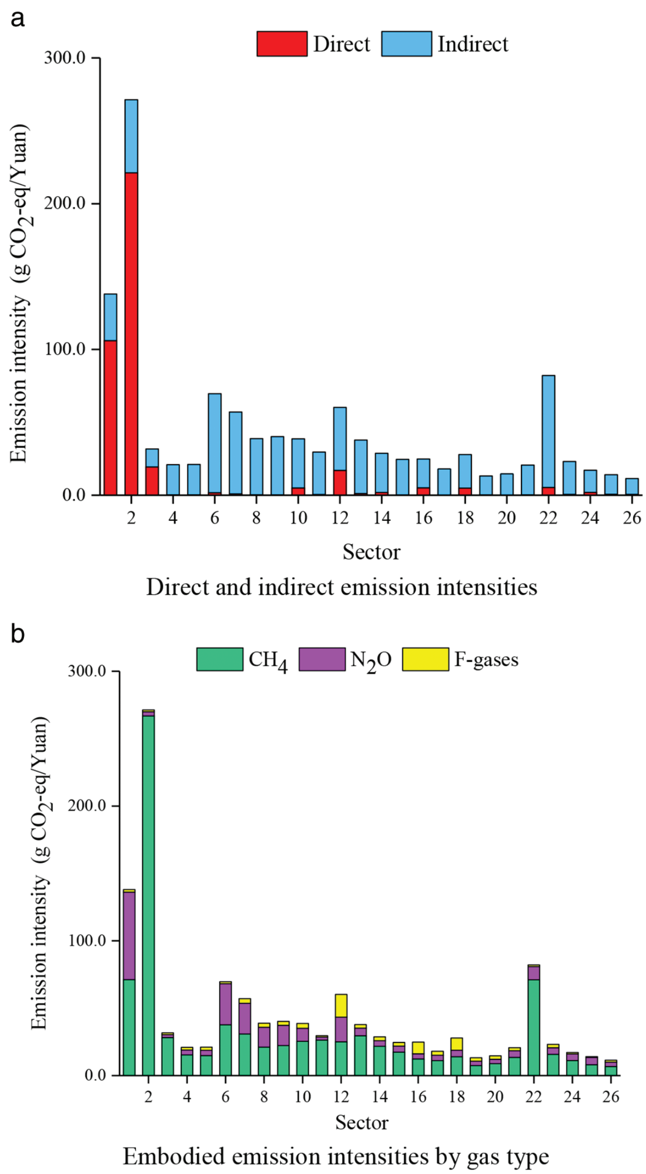

Figure 3. Embodied emission intensities by sector. (a) Direct and indirect emission intensities and (b) embodied emission intensities by gas type.

4. Consumption-Based Non-CO_2 GHG Emissions

4.1. Embodied Emission Intensities

Figure 3a presents a histogram showing the embodied non-CO_2 GHG emission intensities (including direct and indirect emission intensities) by sector in 2012. Apparently, Sectors 2 (*Mining and Washing of Coal*) and 1 (*Farming, Forestry, Animal Production and Fishery*) held the top two embodied emission intensities of 271.3 and 138.0 g CO_2-eq/Yuan, respectively, mainly due to their high direct emission intensities. Indirect emission intensity took a large proportion of embodied emission intensity for most sectors except Sectors 1, 2, and 3, which presents the essential contribution of indirect emissions to the total embodied emission intensities due to inter-industrial input.

The embodied emission intensity can also be divided by the emission type in terms of CH_4, N_2O, and F-gases, as illustrated in Figure 3b. Embodied non-CO_2 emission intensities of most sectors were dominated by CH_4, especially Sector 2, mainly due to massive fugitive CH_4 emissions from coal mining. In many manufacturing and service sectors, CH_4 emissions from solid fuels dominated their embodied emission intensities. N_2O emission intensities also shared important proportions in Sector 1 and several manufacturing sectors. The share of embodied emission intensity of F-gases was especially high in Sector 12 (*Manufacture of Chemicals and Chemical Products*), accounting for 28.0% of the sectoral non-CO_2 emission intensity.

4.2. Embodied Emissions in Final Demand

Figures 4 and 5a present the embodied emissions in final demand in terms of rural consumption, urban consumption, government consumption, capital formation, stock increase, and exports. The four sectors of Sectors 1 (*Farming, Forestry, Animal Production and Fishery*, 20.0% of the total), 23 (*Construction*, 16.0%), 6 (*Manufacture of Food and Tobacco*, 15.2%), and 26 (*Other service activities*, 9.7%) contributed to three-fifths of the total embodied emissions. There were remarkable disparities on the sectoral embodied emissions.

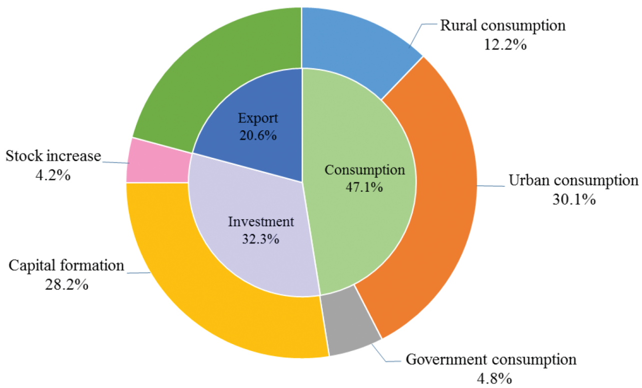

Figure 4. Compositions of embodied emission by Chinese economy.

Consumption contributed the largest fraction of 47.1% to the total embodied emission, which consisted of rural consumption (12.2%), urban consumption (30.1%) and government consumption (4.8%). Consumption-driven emissions were mainly distributed in Sectors 1 (276.5 Mt. CO_2-eq), 6 (252.0 Mt. CO_2-eq) and 26 (153.0 Mt. CO_2-eq), which accounted for 31.4%, 28.6%, and 17.4% of the total embodied emissions in consumption, respectively. These sectors were closely linked with people's life such as food, electricity, heat, and other services. Because of the wide gap between urban and rural household expenditure, and the embodied emissions of urban household consumption were 2.5-fold of those of rural household consumption. In Sector 26, government consumption played as an important final demand category in its embodied emissions.

Investment is made up of capital formation and stock increase. About 87.1% of the investment-driven emissions sourced from capital formation, and the rest was due to stock increase. A large number of investment-driven embodied emissions can be attributed to construction activities which required a great deal of direct and indirect inputs of electricity and building materials (e.g., steel, nonferrous metal, cement, and other nonmetal mineral products) (Chen & Zhang, 2010; Feng et al., 2014). Sectors 23 (49.3%) and 1 (14.4%) were the top two contributors. Some manufacturing sectors such as Sector 16 (*Manufacture of General-Purpose and Special-Purpose Machinery*) also had high investment-driven embodied emissions.

The embodied emissions induced by export summed up to 385.5 Mt. CO_2-eq, accounting for about 20.6% of the national total. For some manufacturing sectors which provided major export products, the export-driven embodied emissions were relatively high. This can be explained by the fact that the structures of China's exports were dominated by metal products, chemical products, textiles products, electric equipment, etc. Export was the leading final demand category in 15 industrial sectors. For instance, in Sectors 12 (*Manufacture of Chemicals and Chemical Products*), 8 (*Manufacture of Textile Wearing Apparel, Footwear, Leather, Fur, Feather and Its Products*), 19 (*Manufacture of Communication Equipment, Computer and Other Electronic Equipment*), and 18 (*Manufacture of Electrical Machinery and Apparatus*), more than 50% of their sectoral embodied emissions can be attributed to export.

Figure 5b presents the distribution of embodied emissions in final demand by gas type. CH_4 was the leading gas in the embodied emissions of all the 26 sectors, especially in Sectors 23 (*Construction*), 1 (*Farming, Forestry, Animal Production and Fishery*), 6 (*Manufacture of Food and Tobacco*), and 26 (*Other Service Activities*). The top three sectors of embodied N_2O emissions were Sectors 1, 6, and 23, whose emissions were less than CH_4. The shares of F-gases were especially high in Sectors 16, 23, 12, and 26. Detailed results are listed in Table S6 in Supporting Information S1.

5. The Supply Chain of Non-CO_2 GHG Emissions

Referring to related studies (Meng et al., 2015; Subramanyam et al., 2015; Zhang et al., 2017a), embodied emission flows throughout entire supply chains in the Sankey diagram can map where the emissions have gone (production attribution), and where the emissions embodied in final products have come from (consumption attribution). Figure 6 illustrates the embodied emissions driven by the final demand at Tier 0, Tier 1, and higher tiers. Table 4 further lists the distribution of demand-driven emission requirements in each production tier along the supply chains. To reduce the complexity, the original 26 sectors were consolidated into eight broad categories: *Agriculture*, *Coal*, *Petroleum & Gas*, *Manufacturing, Power & Heat*, *Construction*, *Transportation*, and *Service*.

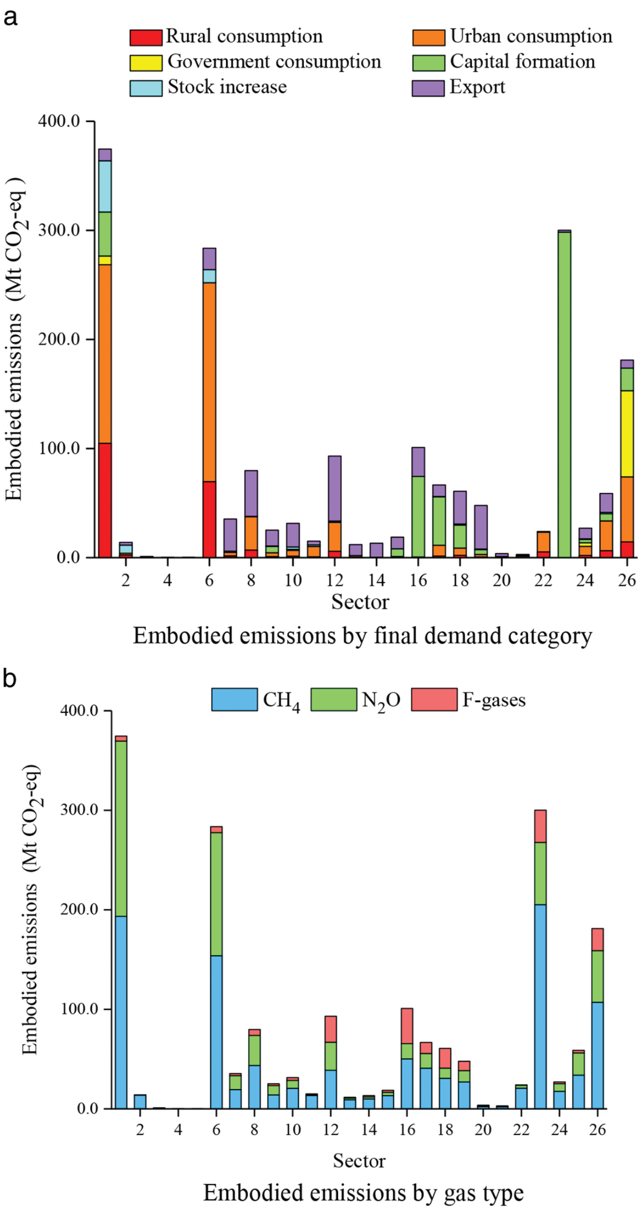

Figure 5. Embodied emissions in final demand by sector. (a) Embodied emissions by final demand category and (b) Embodied emissions by gas type.

From production-oriented perspective, the emissions were dominated by three sectors, that is, *Agriculture* (50.3%), *Coal* (26.8%) and *Manufacturing* (17.8%). From consumption-oriented perspective, *Manufacturing* accounted for 47.6% of the total embodied emissions in final demand, followed by *Agriculture* for 20.0%, *Construction* for 16.0%, and *Service* for 12.8%. The embodied emission fluxes from PL^t can be traced to the eight aggregated sectors, as shown in Figure 6 from right to left. *Agriculture*, *Coal*, and *Petroleum & Gas* at Tier 0 provided the emissions to meet final demand directly, contributing to 76.8%, 81.5%, and 61.4% of their respective total embodied emissions, respectively (see Table 4).

The embodied emissions of *Transportation* appeared to be evenly distributed across the production tiers, mainly due to its complex economic relationships with other sectors. In the *Service* sector, most of the embodied emissions occurred at the second and higher tiers with a similar structure in sectoral contribution. In contrast, *Power & Heat* drove 47.9% of its total embodied emission in Tier 1, and Tier 2 and all the other tiers contributed the remained half. As to *Manufacturing*, direct emissions at PL^0 accounted for only 8.1% (72.2 Mt. CO_2-eq) while the inputs purchased from PL^1 had very high embodied emissions, mainly in *Manufacturing* products (470.2 Mt. CO_2-eq, 52.8%), *Agriculture* (238.6 Mt. CO_2-eq, 26.8%). For the *Agriculture*, the story was quite different. Its direct emissions at PL^0 accounted for 76.8% (287.7 Mt. CO_2-eq) and the inputs from PL^1 highly concentrated in the products of *Agriculture*, accounting for 13.1% (49.1 Mt. CO_2-eq) of the total and *Manufacturing* (33.7 Mt. CO_2-eq,

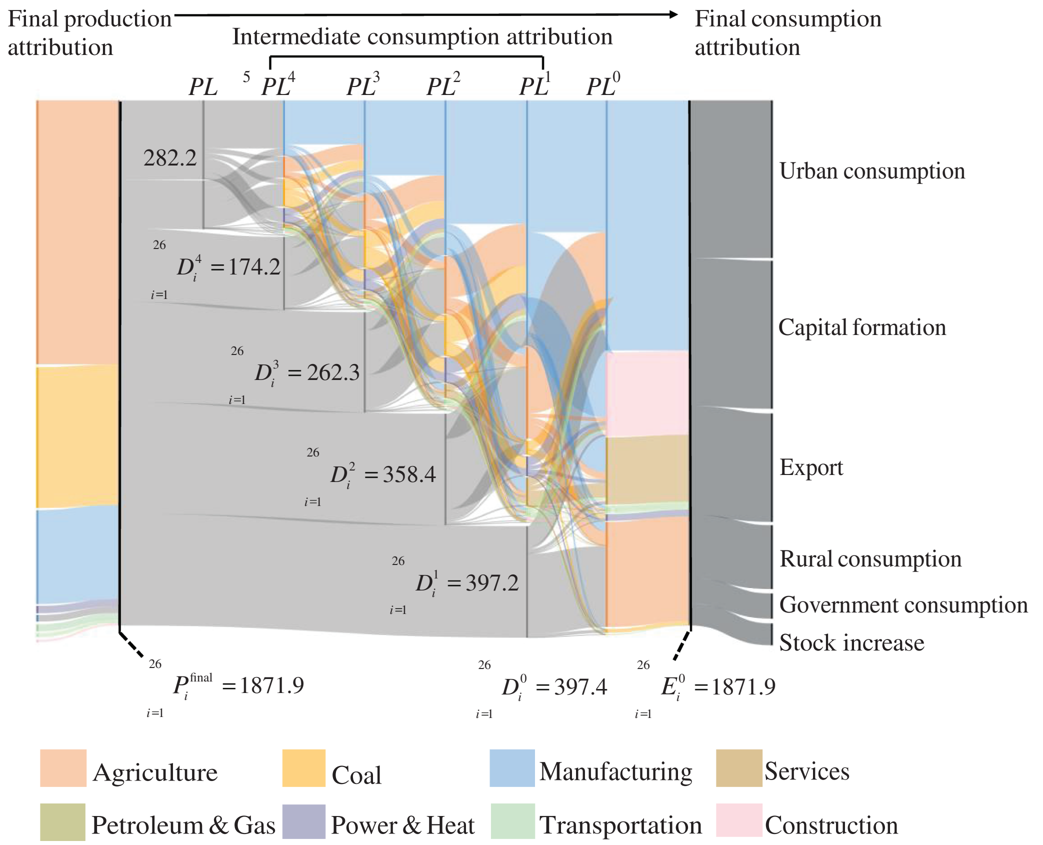

Figure 6. Embodied emission flows throughout entire supply chains in Sankey diagram. Note: From left to right, the widths of indicated flows represent the magnitude of embodied emissions (Unit: Mt. CO_2-eq). The left-hand side of the map shows direct emissions from production (1871.9 Mt. CO_2-eq). Colors indicate the eight aggregated sectors. The central part of the diagram reveals the intermediate consumption attributions of each aggregated sector at PL^1, PL^2, PL^{3+}, and PL^4 which are indicated by the dark gray "flow" linking back to the finial production attribution. An element D_s^t presents direct emission from sector s at PL^t. An element (E_s^t) at PL^t represents embodied emissions in the output of sector s at PL^t. Flow from PL^t to PL^{t-1} ($E_{ij}^{t \to t-1}$) measures embodied emissions from all sectors embodied in the output of sector i at PL^t purchased by sector j at PL^{t-1}. The dark gray "flows" on the right-hand side of map indicate the embodied emissions attributed to final demand (rural consumption, urban consumption, government consumption, capital formation, inventory increase, and export). The sum of embodied emissions in final production equals to the sum of those in final consumption.

9.0%). The inputs of *Construction* purchased from PL^1 also had very high embodied emissions in the *Manufacturing* products with the proportion of 77.3% (231.9 Mt. CO_2-eq). The embodied emissions in *Transportation* and *Service* had similar patterns with those in *Manufacturing* in PL^1. Therefore, final consumption in the eight aggregated sectors had different patterns in inducing embodied emissions in different tiers.

To identify how the final consumption drove emissions in each tier, we extract and rank individual critical supply chains, which start from final demand along the supply chain to the production. Table 5 lists the top 20 paths, through which the final demands drove the production processes, representing 51.7% of the national total embodied emissions. Eight ranking paths were driven by capital formation, seven ranking paths were driven by urban consumption, and four paths by export. The path of "Urban consumption→*Farming, Forestry, Animal Production and Fishery*" contributed the largest share of 15.4%, followed by "Urban consumption→*Manufacture of Food and Tobacco*→*Farming, Forestry, Animal Production and Fishery*" of 8.0%, "Urban consumption→*Manufacture of Food and Tobacco*→*Manufacture of Food and Tobacco*→*Farming, Forestry, Animal Production and Fishery*" of 3.7%, and "Capital formation→*Construction*→*Production and Supply of Electricity and Steam*→*Production and Supply of Electricity and Steam*→*Mining and Washing of Coal*" of 2.2%. The top 10 paths were responsible for 40.3% of the total embodied emissions.

Seven of the top 20 paths were associated with *Construction*, showing that this sector was the important transmission channel for embodied emissions. The sector of *Production and Supply of Electricity and*

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Table 4.
Distribution of Sectoral Embodied Emissions in the Production Tier in 2012

		Attribution of embodied emissions (%)						
Aggregated sector	Embodied emissions (Mt CO_2-eq)	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5 → ∞	Total
Agriculture	374.6	76.8	11.3	5.7	2.8	1.5	1.9	100.0
Coal	14.1	81.5	12.3	3.0	1.3	0.7	1.1	100.0
Petroleum & Gas	1.1	61.4	5.0	12.1	8.5	5.2	7.9	100.0
Manufacturing	890.9	8.1	29.9	21.0	14.9	9.9	16.2	100.0
Power & Heat	24.1	6.5	47.9	23.9	10.5	5.0	6.2	100.0
Construction	300.1	2.7	10.7	25.5	21.7	15.0	24.4	100.0
Transportation	27.0	11.4	13.4	27.7	17.0	11.2	19.3	100.0
Service	240.0	5.3	16.6	25.0	19.2	12.9	21.1	100.0

Steam, which consumed raw coal and provided electricity to other economic sectors or households, was linked with five of the high-ranking paths. Other critical transmission sectors included *Manufacture of Food and Tobacco* and *Manufacture of Chemicals and Chemical Products*. Prominently, 9 of the 20 rankings can be traced back to the *Farming, Forestry, Animal Production and Fishery*, and 7 to the *Mining and Washing of Coal*.

The top 20 paths of specific three gases starting from a final demand and ending with a consuming sector are listed in Tables S7–S9 in Supporting Information S1. For CH_4, most paths were associated with *Production and Supply of Electricity and Steam, Construction* and *Other Service Activities,* and can mainly be traced back to the two sectors of *Mining and Washing of Coal* and *Farming, Forestry, Animal Production and Fishery*. For N_2O, most of the paths were related to *Manufacture of Food and Tobacco* and *Manufacture of Chemicals and Chemical Products*, and mainly traced back to the sector of *Farming, Forestry, Animal Production and Fishery*. For F-gases, *Construction* had a higher frequency, mainly tracing back to *Manufacture of Chemicals and Chemical Products*.

6. Concluding Remarks

In view of the important contribution of China's non-CO_2 GHG emissions to global climate change (Li et al., 2016), increasing non-CO_2 GHGs could offset the country's efforts to mitigate GHG emissions (Zhang et al., 2015). We start with the national input–output analysis based on officially released emission inventory and economic input–output table in 2012 to examine China's non-CO_2 GHG emissions from both production- and consumption-based perspectives. We estimate the contribution of five types of final demand for a wide range of products to the national emissions. Then the SPA further tracked the supply chains of non-CO_2 GHG emissions and identified critical paths and key sectors for emission mitigation.

1. China's non-CO_2 GHG emissions in 2012 amounted to 2003.0 Mt. CO_2-eq (including 1871.9 Mt. CO_2-eq from economic activities), much larger than the total GHG emissions in some developed countries. Agricultural activities, energy activities, industrial processes, and waste management contributed to 50.1%, 31.4%, 14.4%, and 4.1% of the total non-CO_2 GHG emissions from economic activities, respectively. Agricultural activities contributed significantly to the national total emissions of CH_4 and N_2O. Energy activities contributed approximately half of the total CH_4 emissions. Industrial process played a major role in F-gas emissions. The top three economic sectors, that is, *Farming, Forestry, Animal Production and Fishery*, *Mining and Washing of Coal* and *Manufacture of Chemicals and Chemical Products*, were responsible for 50.3%, 26.8%, and 11.0% of the total economy-wide non-CO_2 GHG emissions, respectively.
2. Urban consumption (30.1%), capital formation (28.2%), and exports (20.6%) derived 78.9% of the total embodied emissions in final demand. The four sectors of *Farming, Forestry, Animal Production and Fishery* (20.0% of the total), *Construction* (16.0%), *Manufacture of Food and Tobacco* (15.2%), and *Other*

Table 5.
The Top 20 Supply Chain Paths for non-CO_2 GHG Embodied Emissions in 2012

Rank	Production layer	Contribution (%)	Path
1	0	15.4	Urban consumption → *Farming, Forestry, Animal Production and Fishery*
2	1	8.0	Urban consumption → *Manufacture of Food and Tobacco* → *Farming, Forestry, Animal Production and Fishery*
3	2	3.7	Urban consumption → *Manufacture of Food and Tobacco* → *Manufacture of Food and Tobacco* → *Farming, Forestry, Animal Production and Fishery*
4	3	2.2	Capital formation → *Construction* → *Production and Supply of Electricity and Steam* → *Production and Supply of Electricity and Steam* → *Mining and Washing of Coal*
5	3	2.2	Urban consumption → *Manufacture of Food and Tobacco* → *Manufacture of Food and Tobacco* → *Manufacture of Food and Tobacco* → *Farming, Forestry, Animal Production and Fishery*
6	1	2.0	Urban consumption → *Farming, Forestry, Animal Production and Fishery* → *Farming, Forestry, Animal Production and Fishery*
7	4	1.8	Capital formation → *Construction* → *Production and Supply of Electricity and Steam* → *Production and Supply of Electricity and Steam* → *Production and Supply of Electricity and Steam* → *Mining and Washing of Coal*
8	2	1.8	Rural consumption → *Farming, Forestry, Animal Production and Fishery* → *Farming, Forestry, Animal Production and Fishery* → *Farming, Forestry, Animal Production and Fishery*
9	2	1.7	Capital formation → *Construction* → *Production and Supply of Electricity and Steam* → *Mining and Washing of Coal*
10	2	1.6	Capital formation → *Construction* → *Manufacture of Nonmetallic Mineral Products* → *Mining and Washing of Coal*
11	0	1.4	Export → *Manufacture of Chemicals and Chemical Products*
12	4	1.3	Urban consumption → *Wholesale, Retail Trade, Hotels, Catering Service* → *Manufacture of Food and Tobacco* → *Manufacture of Food and Tobacco* → *Manufacture of Food and Tobacco* → *Farming, Forestry, Animal Production and Fishery*
13	5	1.3	Capital formation → *Construction* → *Production and Supply of Electricity and Steam* → *Production and Supply of Electricity and Steam* → *Production and Supply of Electricity and Steam* → *Production and Supply of Electricity and Steam* → *Mining and Washing of Coal*
14	2	1.2	Capital formation → *Construction* → *Manufacture and Processing of Metals* → *Mining and Washing of Coal*
15	3	1.1	Urban consumption → *Wholesale, Retail Trade, Hotels, Catering Service* → *Manufacture of Food and Tobacco* → *Farming, Forestry, Animal Production and Fishery* → *Farming, Forestry, Animal Production and Fishery*
16	2	1.1	Export → *Manufacture of Chemicals and Chemical Products* → *Manufacture of Chemicals and Chemical Products* → *Manufacture of Chemicals and Chemical Products*
17	0	1.1	Capital formation → *Manufacture of General-Purpose and Special-Purpose Machinery*
18	2	1.1	Export → *Manufacture of Textile Wearing Apparel, Footwear, Leather, Fur, Feather and Its Products* → *Manufacture of Textiles* → *Farming, Forestry, Animal Production and Fishery*
19	3	0.9	Export → *Manufacture of Chemicals and Chemical Products* → *Manufacture of Chemicals and Chemical Products* → *Manufacture of Chemicals and Chemical Products* → *Manufacture of Chemicals and Chemical Products*
20	3	0.9	Capital formation → *Construction* → *Production and Supply of Electricity and Steam* → *Mining and Washing of Coal* → *Mining and Washing of Coal*

service activities (9.7%) contributed to three-fifths of the total embodied emissions. *Construction* had prominent embodied emissions in capital formation. The embodied emissions in three others were mainly concentrated on urban consumption and rural consumption. Given remarkable disparities on embodied emission structure, the main driving forces of sectoral non-CO_2 GHG emissions were industrial production, infrastructure construction, household consumption, exports, and other economic activities.

3. The results of SPA show that the emission patterns of economic sectors in different production layers were very different. The intermediate products and services used by *Manufacturing* reflected the highest embodied emissions, accounting for 47.6% of the national total. Critical embodied emission paths and key economic sectors in supply chains are identified for mitigating non-CO_2 GHG emissions by Chinese economy. The top 20 paths were responsible for 51.7% of the national total embodied emissions. Several industrial sectors such as *Construction*, *Production and Supply of Electricity and Steam*, *Manufacture of Food and Tobacco* and *Manufacture of Chemicals and Chemical Products* played as the important transmission channels, which help shape the supply chain of emission requirements.

China's response to addressing non-CO_2 GHG emissions will have a notable impact on the global GHG emissions. Compared with CO_2 emissions, the Chinese government has paid less attention on non-CO_2 GHGs and has not yet set specific targets. In March 2016, China's 13th Five-Year Plan, outlining the strategic vision for the country in the period of 2016–2020, mentioned that China will control non-CO_2 GHG emissions. Only few policies have been issued specifically for reducing non-CO_2 GHG emissions such as coal-bed methane emissions. Although existing policies have referred to the direct emission reduction on site, consumption-based climate change policy framework deserves to be developed. It is important to investigate all the possible emission-reducing potentials and pathways in production and consumption activities, and suppress unnecessary final demands, which will also have mutual benefits for both local air quality and the climate. Timely, robust, and credible non-CO_2 GHG emission inventories — presented both at production-side and consumption-side levels — will form the crucial backbone for identifying key emission sectors, demand drivers and supply chain paths, and prioritizing mitigation strategies and actions.

Acknowledgments
See Tables S1-S9 in Supporting Information S1 associated with this article. All the emission data by source in the national inventory can be available from the People's Republic of China First BUR on Climate Change at http://www.ccchina.gov.cn/. This study has been supported by the National Natural Science Foundation of China (Grant nos. 71774161, 71403270 and 71373262), and the Foundation of State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology (Grant no. SKL-CRSM16KFC06). Very helpful comments by the anonymous reviewers and the editor are highly appreciated.

References

CESY (2013). *China Environmental Statistical Yearbook 2013*. Beijing, China: China Statistics Press.

Chen, G., & Chen, Z. (2010). Carbon emissions and resources use by Chinese economy 2007: A 135-sector inventory and input–output embodiment. *Communications in Nonlinear Science and Numerical Simulation*, *15*(11), 3647–3732. https://doi.org/10.1016/j.cnsns.2009.12.024

Chen, G., Yang, S., Lv, C., Zhong, J., Wang, Z., Wang, Z., … Xue, L. (2017a). An improved method for estimating GHG emissions from onshore oil and gas exploration and development in China. *Science of the Total Environment*, *574*, 707–715. https://doi.org/10.1016/j.scitotenv.2016.09.051

Chen, G., & Zhang, B. (2010). Greenhouse gas emissions in China 2007: Inventory and input–output analysis. *Energy Policy*, *38*(10), 6180–6193. https://doi.org/10.1016/j.enpol.2010.06.004

Chen, W., Wu, F., Geng, W., & Yu, G. (2017b). Carbon emissions in china's industrial sectors. *Resources, Conservation and Recycling*, *117*, 264–273. https://doi.org/10.1016/j.resconrec.2016.10.008

Climate Change Department of National Development and Reform Commission (CCDNDRC) (2017). *The People's Republic of China first biennial update report on climate change*. Beijing, China: CCDNDRC. http://www.ccchina.gov.cn/archiver/ccchinacn/UpFile/Files/Default/20170124155928346053.pdf

CSY (2013). *China Statistical Yearbook 2013*. Beijing, China: China Statistics Press.

Davis, S. J., Peters, G. P., & Caldeira, K. (2011). The supply chain of CO_2 emissions. *Proceedings of the National Academy of Sciences*, *108*(45), 18554–18559. https://doi.org/10.1073/pnas.1107409108

Dong, F., Yu, B., Hadachin, T., Dai, Y., Wang, Y., Zhang, S., & Long, R. (2018). Drivers of carbon emission intensity change in China. *Resources, Conservation and Recycling*, *129*, 187–201. https://doi.org/10.1016/j.resconrec.2017.10.035

Du, M., Peng, C., Wang, X., Chen, H., Wang, M., & Zhu, Q. (2017). Quantification of methane emissions from municipal solid waste landfills in china during the past decade. *Renewable and Sustainable Energy Reviews*, *78*, 272–279. https://doi.org/10.1016/j.rser.2017.04.082

European Commission, Joint Research Centre (JRC)/ PBL Netherlands Environmental Assessment Agency. (2014), Emission database for global atmospheric research (version 4.2) (EDGAR). Retrieved from: http://edgar.jrc.ec.europe.eu/index.php/.

Fang, X., Velders, G. J., Ravishankara, A. R., Molina, M. J., Hu, J., & Prinn, R. G. (2016). Hydrofluorocarbons (HFCs) emissions in china: An inventory for 2005-2013 and projections to 2050. *Environmental Science & Technology*, *50*(4), 2027–2034. https://doi.org/10.1021/acs.est.5b04376

Feng, K., & Hubacek, K. (2016). Carbon implications of china's urbanization. *Energy, Ecology and Environment*, *1*(1), 39–44. https://doi.org/10.1007/s40974-016-0015-x

Feng, F., Ma, L., Li, Z., & Polenske, K. R. (2014). The implications of china's investment-driven economy on its energy consumption and carbon emissions. *Energy Conversion and Management*, *85*, 573–580.

Guan, D., Liu, Z., Geng, Y., Lindner, S., & Hubacek, K. (2012). The gigatonne gap in china/'s carbon dioxide inventories. *Nature Climate Change*, *2*(9), 672–675. https://doi.org/10.1038/nclimate1560

Hawkins, J., Ma, C., Schilizzi, S., & Zhang, F. (2015). Promises and pitfalls in environmentally extended input–output analysis for china: A survey of the literature. *Energy Economics*, *48*, 81–88. https://doi.org/10.1016/j.eneco.2014.12.002

Huo, H., Zhang, Q., Guan, D., Su, X., Zhao, H., & He, K. (2014). Examining air pollution in china using production- and consumption-based emissions accounting approaches. *Environmental Science & Technology*, *48*(24), 14139–14147. https://doi.org/10.1021/es503959t
Intergovernmental Panel on Climate Change (IPCC) (2006). *The 2006 IPCC guidelines for national greenhouse gas inventories (2006 Guidelines)*. Hayama, Japan: IPCC, Institute for Global Environmental Strategies (IGES).
Intergovernmental Panel on Climate Change (IPCC) (2014). *IPCC Fifth Assessment Report: Climate Change 2013 (AR5)*. Cambridge, NY: IPCC http://www.ipcc.ch/index.htm/
Lenzen, M. (2016). Structural analyses of energy use and carbon emissions – An overview. *Economic Systems Research*, *28*(2), 119–132. https://doi.org/10.1080/09535314.2016.1170991
Li, B., Gasser, T., Ciais, P., Piao, S., Tao, S., Balkanski, Y., … Zhou, F. (2016). The contribution of china's emissions to global climate forcing. *Nature*, *531*(7594), 357–361. https://doi.org/10.1038/nature17165
Liu, L. J., & Liang, Q. M. (2017). Changes to pollutants and carbon emission multipliers in China 2007–2012: An input-output structural decomposition analysis. *Journal of Environmental Management*, *203*(Part 1), 76–86.
Ma, Z., & Gao, Q. (2011). *Guidelines for Calculating GHG Emissions of Waste Disposal*. Beijing, China: Science Press.
Meng, J., Liu, J., Guo, S., Huang, Y., & Tao, S. (2016). The impact of domestic and foreign trade on energy-related PM emissions in Beijing. *Applied Energy*, *184*, 853–862. https://doi.org/10.1016/j.apenergy.2015.09.082
Meng, J., Liu, J., Xu, Y., & Tao, S. (2015). Tracing primary $PM_{2.5}$ emissions via Chinese supply chains. *Environmental Research Letters*, *10*(5), 054005. https://doi.org/10.1088/1748-9326/10/5/054005
Meng, J., Mi, Z., Yang, H., Shan, Y., Guan, D., & Liu, J. (2017). The consumption-based black carbon emissions of china's megacities. *Journal of Cleaner Production*, *161*, 1275–1282. https://doi.org/10.1016/j.jclepro.2017.02.185
Miller, R. E., & Blair, P. D. (2009). *Input-output analysis: foundations and extensions* (2nd ed.). Cambridge, England: Cambridge University Press. https://doi.org/10.1017/CBO9780511626982
Montzka, S. A., Dlugokencky, E. J., & Butler, J. H. (2011). Non-CO_2 greenhouse gases and climate change. *Nature*, *476*(7358), 43–50. https://doi.org/10.1038/nature10322
National Bureau of Statistics of China (NBSC) (2015a). *2012 Input-output table of China*. Beijing, China: Statistics Press.
National Bureau of Statistics of China (NBSC) (2015b). *China Energy statistical yearbook 2014*. Beijing, China: Statistics Press.
Peng, S., Piao, S., Bousquet, P., Ciais, P., Li, B., Lin, X., … Zhou, F. (2016). Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010. *Atmospheric Chemistry and Physics*, *16*(22), 14545–14562. https://doi.org/10.5194/acp-16-14545-2016
Peters, G. P. (2008). From production-based to consumption-based national emission inventories. *Ecological Economics*, *65*(1), 13–23. https://doi.org/10.1016/j.ecolecon.2007.10.014
Skelton, A., Guan, D., Peters, G. P., & Crawford-Brown, D. (2011). Mapping flows of embodied emissions in the global production system. *Environmental Science & Technology*, *45*(24), 10516–10523. https://doi.org/10.1021/es202313e
Subramanyam, V., Paramshivan, D., Kumar, A., & Mondal, M. A. H. (2015). Using Sankey diagrams to map energy flow from primary fuel to end use. *Energy Conversion and Management*, *91*(91), 342–352. https://doi.org/10.1016/j.enconman.2014.12.024
Tang, X., Jin, Y., Feng, C., & McLellan, B. C. (2018). Optimizing the energy and water conservation synergy in China: 2007–2012. *Journal of Cleaner Production*, *175*, 8–17. https://doi.org/10.1016/j.jclepro.2017.11.100
United States Environmental Protection Agency (USEPA). (2012), EPA report 430-R-12-006, global anthropogenic non-CO_2 GHG missions: 1990–2030. Retrieved from: http://www.epa.gov/climatechange/Downloads/EPAactivities/EPA_Global_NonCO2_Projections_Dec2012.pdf
Wang, L., Xue, B., & Yan, T. (2017a). Greenhouse gas emissions from pig and poultry production sectors in China from 1960 to 2010. *Journal of Integrative Agriculture*, *16*(1), 221–228. https://doi.org/10.1016/S2095-3119(16)61372-2
Wang, Z., Wei, L., Niu, B., Liu, Y., & Bin, G. (2017b). Controlling embedded carbon emissions of sectors along the supply chains: A perspective of the power-of-pull approach. *Applied Energy*, *206*, 1544–1551. https://doi.org/10.1016/j.apenergy.2017.09.108
World Bank. (2017), World Bank database: Indicators, climate change. Retrieved from: https://data.worldbank.org/
Wu, X. F., & Chen, G. Q. (2017). Energy use by Chinese economy: A systems cross-scale input-output analysis. *Energy Policy*, *108*, 81–90.
Yang, R., Zhu, T., & Gao, Q. (2014). *Technologies and policy recommendations for emission reduction of non-CO_2 greenhouse gas from typical industries in China*. Beijing, China: China Environmental Science Press.
Yang, Z., Dong, W., Xiu, J., Dai, R., & Chou, J. (2015). Structural path analysis of fossil fuel based CO_2 emissions: A case study for China. *PLoS One*, *10*(9), e0135727. https://doi.org/10.1371/journal.pone.0135727
Yao, B., Ross, K., Zhu, J., Igusky, K., Song, P., & Damassa, T. (2016). *Opportunities to enhance non-CO_2 greenhouse gas mitigation in China*. Working Paper. Washington, DC: World Resources Institute Retrieved from: http://www.wri.org/sites/default/files/Opportunities_to_enhance_non-CO2_GHG_mitigation_in_China.pdf
Yuan, R., Behrens, P., & Rodrigues, J. F. D. (2017). The evolution of inter-sectoral linkages in China's energy-related CO_2 emissions from 1997 to 2012. *Energy Economics*, *69*, 404–417. https://doi.org/10.1016/j.eneco.2017.11.022
Yuko, O. (2012). Identifying critical supply chain paths that drive changes in CO_2 emissions. *Energy Economics*, *34*(4), 1041–1050.
Zhang, B., & Chen, G. (2010). Methane emissions by Chinese economy: Inventory and embodiment analysis. *Energy Policy*, *38*(8), 4304–4316. https://doi.org/10.1016/j.enpol.2010.03.059
Zhang, B., & Chen, G. (2014). Methane emissions in China 2007. *Renewable and Sustainable Energy Reviews*, *30*, 886–902. https://doi.org/10.1016/j.rser.2013.11.033
Zhang, B., Chen, G., Li, J., & Tao, L. (2014a). Methane emissions of energy activities in China 1980–2007. *Renewable and Sustainable Energy Reviews*, *29*(7), 11–21. https://doi.org/10.1016/j.rser.2013.08.060
Zhang, B., Chen, Z., Qiao, H., Chen, B., Hayat, T., & Alsaedi, A. (2015). China's non-CO_2 greenhouse gas emissions: Inventory and input–output analysis. *Ecological Informatics*, *26*(10), 101–110. https://doi.org/10.1016/j.ecoinf.2014.01.009
Zhang, B., Li, J., & Peng, B. (2014b). Multi-regional input-output analysis for China's regional CH_4 emissions. *Frontiers in Earth Science*, *8*(1), 163–180. https://doi.org/10.1007/s11707-014-0408-0
Zhang, B., Peng, S., Xu, X., & Wang, L. (2011). Embodiment analysis for greenhouse gas emissions by Chinese economy based on global thermodynamic potentials. *Energies*, *4*(11), 1897–1915. https://doi.org/10.3390/en4111897
Zhang, B., Qu, X., Meng, J., & Sun, X. (2017a). Identifying primary energy requirements in structural path analysis: A case study of China 2012. *Applied Energy*, *191*, 425–435. https://doi.org/10.1016/j.apenergy.2017.01.066
Zhang, B., Yang, T., Chen, B., & Sun, X. (2016). China's regional CH_4 emissions: Characteristics, interregional transfer and mitigation policies. *Applied Energy*, *184*, 1184–1195. https://doi.org/10.1016/j.apenergy.2016.04.088
Zhang, J., Yu, B., Cai, J., & Wei, Y. (2017b). Impacts of household income change on CO_2 emissions: An empirical analysis of China. *Journal of Cleaner Production*, *157*, 190–200. https://doi.org/10.1016/j.jclepro.2017.04.126