Socioeconomic determinants of China's growing CH_4 emissions

Abstract

Reducing CH_4 emissions is a major global challenge, owing to the world-wide rise in emissions and concentration of CH_4 in the atmosphere, especially in the past decade. China has been the greatest contributor to global anthropogenic CH_4 emissions for a long time, but current understanding towards its growing emissions is insufficient. This paper aims to link China's CH_4 emissions during 2005-2012 to their socioeconomic determinants by combining input-output models with structural decomposition analysis from both the consumption and income perspectives. Results show that changes in household consumption and income were the leading drivers of the CH_4 growth in China, while changes in efficiency remained the strongest factor offsetting CH_4 emissions. After 2007, with the global financial crisis and economic stimulus plans, embodied emissions from exports plunged but those from capital formation increased rapidly. The enabled emissions in employee compensation increased steadily over time, whereas emissions induced from firms' net surplus decreased gradually, reflecting the reform on income distribution. In addition, at the sectoral level, consumption and capital formation respectively were the greatest drivers of embodied CH_4 emission changes from agriculture and manufacturing, while employee compensation largely determined the enabled emission changes across all industrial sectors. The growth of CH_4 emissions in China was profoundly affected by the macroeconomic situation and the changes of economic structure. Examining economic drivers of anthropogenic CH_4 emissions can help formulate comprehensive mitigation policies and actions associated with economic production, supply and consumption.

Keywords: China's CH_4 emissions; Consumption-based accounting; Income-based accounting; Input-output analysis; Structural decomposition analysis

1 Introduction

China is one of the countries most vulnerable to the adverse impacts of climate change. However, it is also the largest CO_2 emitter in the world (Li et al., 2016). China' rapidly increasing CO_2 emissions have prompted the measures to address climate change and to achieve emission mitigation. The country's government has pledged to lower its CO_2 emissions per unit of GDP by 60-65% relative to the 2005 level and committed to peak its CO_2 emissions by around 2030. A series of energy and climate policies have been developed and implemented to ensure such mitigation targets. Nevertheless, most of these policies and actions have focused on the reduction of CO_2 emissions.

Methane (CH_4) is the second largest greenhouse gas (GHG) after CO_2, but is more active than the latter. For a time horizon of 20 years, CH_4 has greater short-term climate impacts than CO_2 with a Global Warming Potential 84 times larger than CO_2 (IPCC, 2014), while it is responsible for nearly one fifth of global warming (Montzka et al., 2011). In the recent decade, the atmospheric concentration of CH_4 has witnessed a disturbing surge (Saunois et al., 2016) to the extent that it has more than doubled compared with the level before the Industrial Revolution. The growth of CH_4 levels in the atmosphere has been largely driven by increasing emissions from human activities such as agricultural activities and fossil fuel extraction, and then mitigation of anthropogenic CH_4 emissions can generate direct effects on its atmospheric concentration (e.g., Ghosh et al., 2015; Nisbet et al., 2016) .

China is the world's largest contributor of anthropogenic CH_4 emissions. To date, there are three national GHG inventories including CH_4 emissions reported by the Chinese government (CCDNDRC, 2017; Zhang et al., 2018a). According to the last official national GHG inventory, which was published in the first Biennial Update Report (BUR) on Climate Change submitted to the UNFCCC (CCDNDRC, 2017), China's total CH_4 emissions amounted to 55.9 Tg in 2012. Even by the lower GWP value of 21, this amount was equal to 1174 Mt CO_2-eq, much larger than the CO_2 emissions in some developed countries such as England and Japan. In view of the importance of CH_4 in the whole GHG emission inventories, China's significant CH_4 emissions have attracted considerable research in inventory compilation and analysis over the last decade. Some researchers and international institutions have published their own estimates for China's CH_4 emissions at the national scale (e.g., USEPA, 2012; Yang et al., 2014; Zhang and Chen, 2014; Zhang et al., 2014; Peng et al., 2016; Janssens-Maenhout et al. 2017). All unanimously reported that China's CH_4 emissions had witnessed dramatic increases over the past three decades (Zhang, 2011; Peng et al., 2016). Recently, the EDGAR database provided a consistent series of China's CH_4 emissions inventory covering 1970-2012 (EDGAR, 2017). Existing emission inventories have identified the surge in livestock, energy and waste-related CH_4 emissions in China, especially since 2005, as well as how this fast growing trend is unlikely to be reversed in the near periods (Yao et al., 2016). Given the severe challenges that increasing CH_4 emissions poses in mitigating GHG emissions, more attention should be paid to understanding and quantifying China's CH_4 emissions and to propose potential mitigation measures.

In China, CH_4 emissions are directly related to economic production such as energy extraction and supply (Zhang et al., 2014), rice cultivation and livestock farming (Wang et al., 2017b), and waste management services (Du et al., 2017, 2018b). Besides mitigating CH_4 emissions on the production side, it is essential to understand the role of socioeconomic activities in anthropogenic emissions and reveal the opportunities available for mitigation (Zhang et al., 2015; Zhou et al., 2018). It is widely acknowledged that resource extraction and environmental emissions are induced by final consumption demand (Liu et al., 2010; Wu and Chen, 2017; Tang et al., 2018). Environmentally extended input-output analysis (EEIOA) facilitates a deeper appreciation of sector-specific direct/visible and indirect/hidden emission requirements (Miller and Blair, 2009). By using the Leontief demand-driven input-output models, a series of studies have been performed to measure consumption-based accounting of GHG emissions at different scales (Feng et al., 2015; Hawkins et al., 2015). An increasing amount of literature has focused on China's CO_2 emissions embodied in final consumption and international trade (e.g., Chen and Zhang, 2010; Feng et al., 2012; Yuan et al., 2018).

Particularly, Zhang and his colleagues (Zhang and Chen, 2010; Zhang et al., 2015, 2018a) have conducted a series of studies on the embodiment analysis of CH_4 emissions in China. Environmental emissions can also be driven by primary inputs. Higher income translates to higher consumption capacity and greater demands for environmental resource inputs. The Ghosh supply-push input-output model can capture the linkages of value-added with primary inputs, which has been used to estimate the enabled emissions of CO_2 and air pollutants driven by the value added using the income-based accounting method (e.g., Liu et al., 2010; Zhang, 2010; Marques et al., 2013; Liang et al., 2016a,b; Liu and Fan, 2017). Furthermore, the method of structural decomposition analysis (SDA) enables researchers to examine the driving forces of resources, emissions and other physical quantities (e.g., Hoekstra and Van Den Bergh, 2002; Su and Ang, 2012, 2017; Arto and Dietzenbacher, 2014; Malik et al., 2016; Deng and Xu, 2017; Wang et al., 2017a). By using this method, energy, air pollutants and carbon emissions in China have been widely analyzed (e.g., Kagawa and Inamura, 2004; Peters et al., 2007; Guan et al., 2008, 2009, 2014; Zhang, 2009; Xu et al., 2011; Zhang and Qi, 2011; Feng et al., 2012, 2017; Xie, 2014; Zeng et al., 2014; Deng et al., 2016; Yuan and Zhao, 2016; Jiao et al., 2017; Liu and Liang, 2017; Mi et al., 2017a, 2017b; Shi et al., 2017; Wei et al., 2017; Zhao et al., 2017; Du et al., 2018a; Zhang et al., 2018b). Despite of the existing literature on GHG emissions accounting, the current understanding of China's CH_4 emissions from both consumption- and income-based perspectives is insufficient.

Exploring and explaining the socio-economic drivers behind China's growing anthropogenic CH_4 emissions is of critical importance for three reasons. First, China has not only been the largest CH_4 emitter in the world, its level of emissions has also increased constantly. Identifying major emission drivers provides guidance on further mitigation. Second and more importantly, the world-wide rise in CH_4 emissions over the last decade is poorly understood. Unlike CO_2 emissions, there is an ongoing dispute over the determinants of the surging atmospheric CH_4. Various sources have been suggested to be responsible for this increase, such as agricultural activities in Asia (Schaefer et al., 2016), feedback effects from tropical wetlands (Nisbet et al., 2016), and declines in hydroxyl radicals (Turner et al., 2017), yet no consensus has been reached. Surprisingly, explaining CH_4 emission growth with socio-economic factors barely draws any attention from researchers, even though atmospheric CH_4 is closely associated with human activities. Third, CH_4 monitoring is especially inadequate. Although some developed countries have refined their CH_4 measurement equipment to monitor emissions from various sources, upgrading to better equipment for monitoring individual sources is costly for developing countries. Therefore, analyzing the socio-economic drivers of CH_4 emissions and their corresponding mitigation potentials is not only meaningful but is also a practical option for most developing countries with limited resources.

This paper aims to shed light on the issue of China's anthropogenic CH_4 emissions, and explore the socioeconomic determinants of its growing emissions from 2005 (the baseline for China's emission reduction commitment) to 2012 based on the EEIOA and SDA methods. Key sectors and driving forces for embodied and enabled CH_4 emissions in China are identified by using income-based accounting and consumption-based accounting, where the former involves a supply-side SDA and the latter a demand-side SDA. The main contribution of our work is to reveal the supply- and demand-side impacts on anthropogenic CH_4 emissions arising from structural changes in the economy. Finally, we discuss the development of emission trend and future mitigation policies, especially in the economic "new normal".

2 Methodology and data sources

2.1 Consumption-based accounting and structural decomposition analysis

Consumption-based accounting covers the embodied CH_4 emissions caused by final demand (e.g., rural and urban consumption, government consumptiion, investment and export) and relocates the emission responsibility to final consumers. Performing structural decomposition on embodied emissions can provide a comprehensive understanding towards the socioeconomic determinants of CH_4 emissions from the demand side. According to the principle of EEIOA model, e denotes a row vector of sector-level CH_4 emissions and x denotes the sector-level output vector, the CH_4 emissions embodied in final demand, u, can be calculated as

$$u = (e'\hat{x}^{-1})(I - Z\hat{x}^{-1})^{-1}\hat{y} \tag{1}$$

where Z is the inter-sectoral transaction matrix denoting the monetary relationship among different sectors of the economy; y is the vector of final demand for each sector; and the operator $\hat{}$ represents a diagonalizing matrix. The term $e'\hat{x}^{-1}$ stands for a vector of sector-level CH_4 emission intensities, and $(I - Z\hat{x}^{-1})^{-1}$ is the Leontief inverse matrix. Since y represents the final demand, $(I - Z\hat{x}^{-1})^{-1}\hat{y}$ can be interpreted as the inputs from each sector to produce the final demand. Thereafter, embodied CH_4 emissions induced by any given final demand category such as consumption, can be obtained through Equation (1).

We consider five factors, i.e. population, production efficiency, production input structure, consumption structure and absolute consumption volume, for analyzing the determinants of embodied CH_4 emissions. Consequently, the CH_4 emissions embodied in final demand can be decomposed into five terms by rewriting Equation (1) into:

$$u = F \times L \times \hat{p} \times \hat{y}_s \times \hat{y}_v \tag{2}$$

where $F = e'\hat{x}^{-1}$ is the emission intensity which represents production efficiency, and $L = (I - Z\hat{x}^{-1})^{-1}$ represents the linkage between final demand and total output, therefore suggesting the production input structure of the economy. The final demand is decomposed into three terms $y = \hat{p} \times \hat{y}_s \times \hat{y}_v$. Here p is a scalar denoting total population; y_s represents per capita consumption patterns; and y_v stands for per capita consumption of each final demand category.

Performing a structural decomposition analysis on Equation (2) yields:

$$\begin{aligned}\Delta u =& \Delta F \times L \times \hat{p} \times \hat{y}_s \times \hat{y}_v + F \times \Delta L \times \hat{p} \times \hat{y}_s \times \hat{y}_v + F \times L \times \Delta\hat{p} \times \hat{y}_s \times \hat{y}_v \\ & + F \times L \times \hat{p} \times \Delta\hat{y}_s \times \hat{y}_v + F \times L \times \hat{p} \times \hat{y}_s \times \Delta\hat{y}_v \end{aligned} \tag{3}$$

where Δx denotes the change in x. Each of the five components with Δx in the right hand side of the equation represents the contribution to CH_4 emission changes triggered from the changes of x, where all other components remain constant.

The structural decomposition analysis on the input-output model is subject to the non-uniqueness problem since there are 120 alternatives for any decomposition with 5 factors. To address this issue, we follow Dietzenbacher and Los (1998) and Hoekstra and Van Den Bergh (2002) to use the average of all possible first-order decomposition alternatives as the contribution of each component.

2.2 Income-based accounting and structural decomposition analysis

Income-based accounting evaluates the downstream CH_4 emissions enabled by primary inputs (e.g., supplies of labor forces and capital), which accounts for the emissions embodied in the value-added chain. Besides the demand function, the value-added function can be employed to capture the functioning of the EEIOA model from the perspective of income-based accounting. The value-added enabled emissions can be measured as

$$d = \hat{v}(I^{-1} - \hat{x}^{-1}Z)^{-1}(\hat{x}^{-1}e) \tag{4}$$

where v is the vector of value-added, and $(I^{-1} - \hat{x}^{-1}Z)^{-1}$ is the Ghosh inverse matrix that links value-added with primary inputs. Therefore, the right-hand side of Equation (4) amounts to the enabled CH_4 emissions triggered by intermediate input demand.

Because the difference between consumption-based and income-based measure is the emission induced by either final demand or intermediate input demand, the quantity of gross emissions remains unchanged, i.e. $\sum e_i = \sum u_i = \sum d_i$.

The structural decomposition on enabled emissions can further identify the socioeconomic determinants of China's increasing CH_4 emissions from the supply side. Similarly, we decompose the income-based measure into five terms in terms of total population, per capita income, the input structure, production output structure and production efficiency, as follows

$$d = \hat{p} \times \hat{v}_s \times \hat{v}_d \times G \times F \tag{5}$$

where $G = (I^{-1} - \hat{x}^{-1}Z)^{-1}$ and $\hat{v} = \hat{p} \times \hat{v}_s \times \hat{v}_d$. The scalar p again denotes total population; v_s stands for the input structure vector, whose element v_{s_i} indicates the share of sector i's inputs to gross income; v_d stands for per capita income; the matrix G denotes production output structure; and F represents production efficiency.

The structural decomposition form of Equation (5) can be written as:

$$\begin{aligned}\Delta d =& \Delta\hat{p} \times \hat{v}_s \times \hat{v}_d \times G \times F + \hat{p} \times \Delta\hat{v}_s \times \hat{v}_d \times G \times F + \hat{p} \times \hat{v}_s \times \Delta\hat{v}_d \times G \times F \\ &+ \hat{p} \times \hat{v}_s \times \hat{v}_d \times \Delta G \times F + \hat{p} \times \hat{v}_s \times \hat{v}_d \times G \times \Delta F \end{aligned} \tag{6}$$

We use the same approach by calculating the average of all possible first-order decompositions to tackle with the non-uniqueness problem.

2.3 Data sources

The empirical design involves two kinds of dataset: time-series input-output tables and sector-level CH_4 emissions. We obtain the deflated national IO tables for 2005, 2007, 2010 and 2012 from Mi et al. (2017a). They employed double deflation method to deflate the input-output tables. More specifically, they used price indices from China Statistical Yearbook to deflate input-output tables. The real value-added was calculated by the difference between real output and real intermediate inputs to balance the IO tables. Based on the deflated results, all the data of input-output tables were aggregated into 20 economic sectors. Sectoral aggregation provides the convenience of presenting and analyzing empirical results, meanwhile it has limited impacts on our decompositions, because CH_4 emissions are largely concentrated in three sectors (Agriculture, Mining and Other service), and little heterogeneity exists among the merged sectors. Detailed procedures to illustrate the compilation process of the input-output tables at 2012 constant prices can be referred to Mi et al. (2017a).

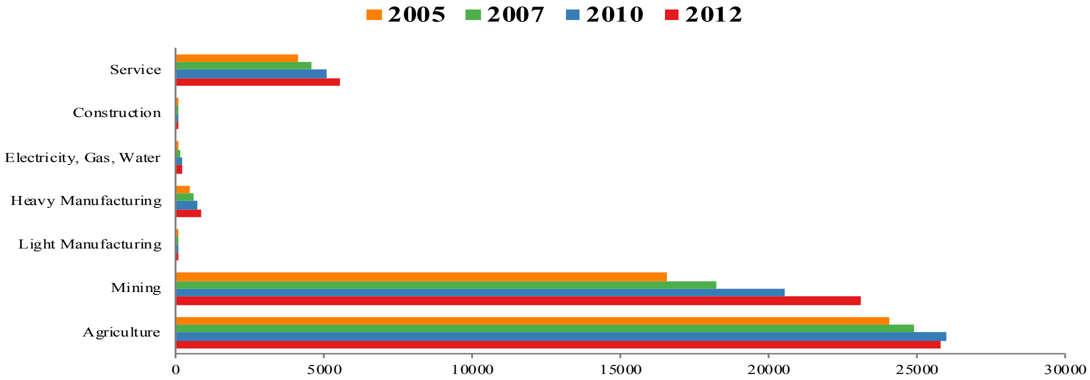
In this study, the inventories of China's anthropogenic CH_4 emissions from the EDGAR 4.3.2 database (EDGAR, 2017; Janssens-Maenhout et al., 2017) are adopted directly. The time-series emission inventories make it possible for a more systematic study on China's CH_4 emissions via the methods of EEIOA and SDA with more strength consistency. We use the time series CH_4 inventories from the EDGAR database to link the industrial sectors of input-output tables directly. The emissions of CH_4 originate from a wide variety of anthropogenic sources, including enteric fermentation, manure management, rice cultivation, coal mining, oil and gas system leakage, fuel combustion, landfills, wastewater treatment, etc. The EDGAR database reports China's detailed CH_4 emissions for more than 80 sources. We merge them into related economic sectors and obtain the sector-level CH_4 emissions. It is worth noting that the uncertainties of input-output analysis can be affected by the accuracy of emission data, especially for developing countries with limited official national GHG inventories. Authoritative time-series inventories of GHG emissions at the national level in the future will improve the performance of EEIOA and SDA models and reduce the uncertainties.

3 Results

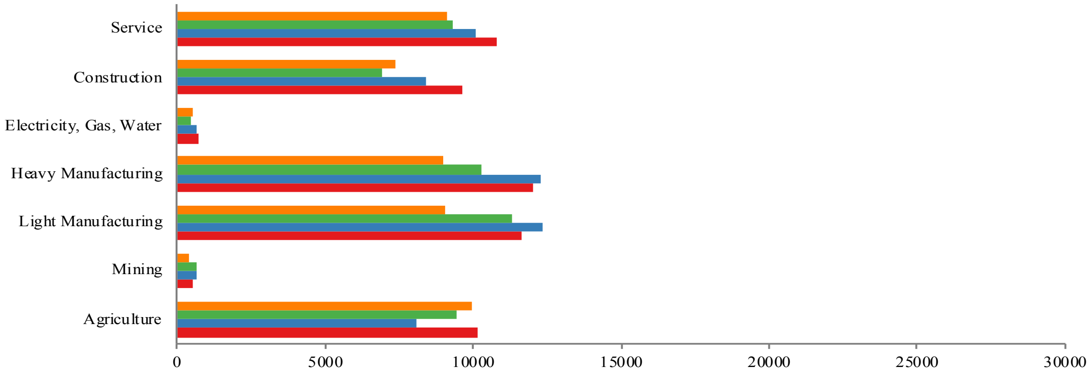
3.1 Direct and indirect CH_4 emission features

In Figure 1, we employ production-based, consumption-based and income-based accounting to quantitatively analyze the dynamics of CH_4 emissions in different sectors. The 13 manufacturing sectors are classified into light and heavy industry sectors for the convenience of presenting the dynamic patterns. The aggregate CH_4 emissions were 45370 Gg in 2005 and grew to 55440 Gg in 2012. Agriculture was the greatest direct contributor to CH_4 emissions, accounting for 47% of national emissions in 2012, although its emissions grew at a moderate rate (7%). Mining was the second largest CH_4 direct emitter, whose emissions grew nearly 40% (from 16576 Gg to 20371 Gg) over the same period. Another important contributor was the service sector, and its direct emissions grew steadily from 3858 Gg to 5020 Gg. These three sectors altogether accounted for 97% of the total national emissions. Other sectors had negligible direct CH_4 emissions.

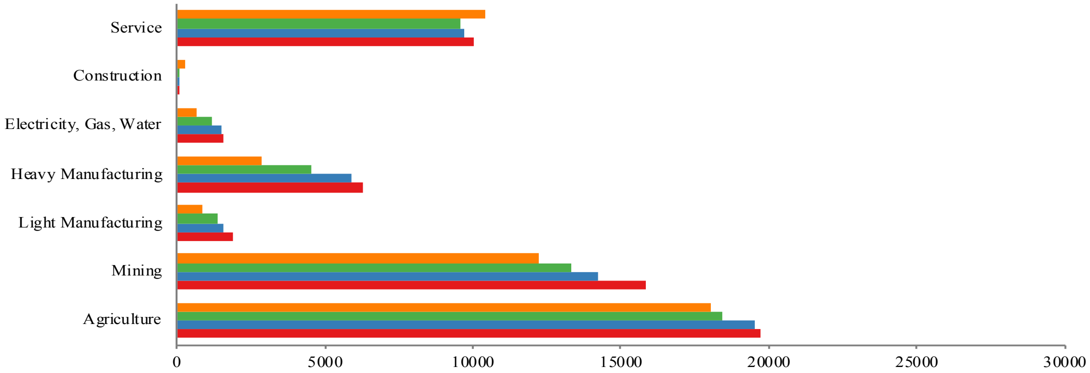
For consumption-based accounting, the contribution of Agriculture was significantly smaller, only accounting for 18% of the total emissions in 2012. More than half of the emissions from this sector are transferred to the production processes of Light Manufacturing and Service as primary material inputs, which highlights the crucial role of Agriculture in providing food, fiber and other plant or animal products for the intermediate use in other industrial sectors. The contribution of Mining decreased to almost zero, suggesting that the Mining sector was more important as a direct emitter of CH_4 emissions than final consumer that induced upstream emissions. Meanwhile, the Manufacturing sectors claimed to be the largest contributor of consumption-based emissions, accounting for 43% of the total emissions in 2012. For both heavy and light manufacturing sectors, their embodied emissions experienced dramatic increase from 2005 to 2010 and slightly decreased in 2012. The production processes of manufacturing required CH_4-intensive intermediate inputs from the Agriculture and Mining sectors. Construction was another major embodied CH_4 emission



(a) Production-based CH_4 emissions (Gg)



(b) Consumption-based CH_4 emissions (Gg)



(c) Income-based CH_4 emissions (Gg)

Figure 1: Direct, embodied and enabled CH_4 emissions of 7 general sectors

sector. It can be explicated that construction sector has high demand for cement, steel, wood and other building materials, which incurs large indirect CH_4 emissions.

In terms of income-based accounting, Agriculture regained its dominant role as a major CH_4 emitter, despite that it contributed less to total enabled emissions compared with its direct emissions. Furthermore, the two different emission measures for Agriculture shared similar moderate growth trends. Mining also remained the second largest income-based emission sector and grew at a steady rate from 12220 Gg to 15850 Gg. Although the anabled emissions of Manufacturing sectors were increasing over time, their contribution to aggregate income-based emissions was significantly smaller than the consumption-based emissions, suggesting the CH_4 emissions of manufacturing sectors were mainly incurred by final demands instead of intermediate inputs. For the Construction sector, it had negligible income-based emissions. This again emphasizes the role of construction sector as a final consumer instead of primary supplier. No matter what accounting approaches are used, the Service sector accounted for 10% to 20% of the national total enabled or embodied emissions, indicating that Service played equally important roles as primary suppliers and final consumers.

Overall, Figure 1 not only displays the constantly increasing trend of CH_4 emissions in China, but also highlights the sharp distinction in consumption- and income-based measures, which further underlines the importance of conducting decomposition analysis from both demand and supply sides.

3.2 Structural changes in consumption-based CH_4 emissions

Figure 2 presents the determinants of consumption-based emission changes. The aggregate CH_4 emissions increased more than 20% from 2005 to 2012, with an annual growth rate about 3%. The greatest driver of this aggregate emission change was the change in per capita consumption, which increased emissions almost 50% during the study period. China kept a rapid economic growth rate with an annual average at 10.7%, and national household consumption grew even more aggressively, i.e. 150% from 2005 to 2012. This surging residential consumption drove up embodied emissions in two ways. On the one hand, the increasing food consumption boosted the growth of CH_4 emissions since Agriculture was the major CH_4 direct emitter. On the other hand, the consumption of other commodities and services also escalated the growth rate of CH_4 emissions, because production of other commodities required intermediate inputs from direct CH_4-intensive sectors (i.e. Agriculture and Mining).

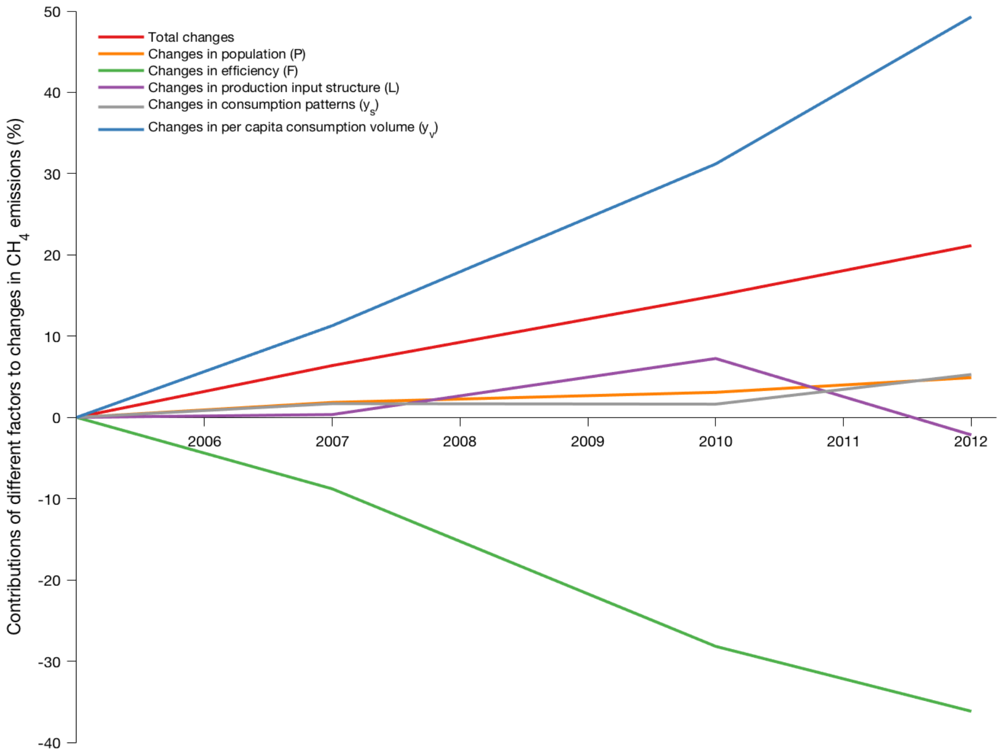


Figure 2: Contributions of different factors to changes in embodied CH_4 emissions

Meanwhile, the efficiency gains offset a large magnitude of CH_4 emission growth (about 35%). Technology progress significantly increased productivity, which suggests firms were able to use fewer inputs to produce the same amount of outputs, therefore inducing fewer CH_4 emissions. Other factors were less important in driving the emission growth. Population changes only increased 5% of CH_4 emissions from 2005 to 2012. The impacts of production input structure on the emission growth were increasing until 2010. After that, its impacts diminished to negative in 2012. This structural change coincided with the "new normal" period during which China put more emphasis on transforming economic development mode and restructuring the economy for balanced and sustainable development. Furthermore, for the consumption structure, it increased at a rather small rate before 2010 and then at a faster pace, reflecting the shift in household consumption towards more CH_4 intensive goods.

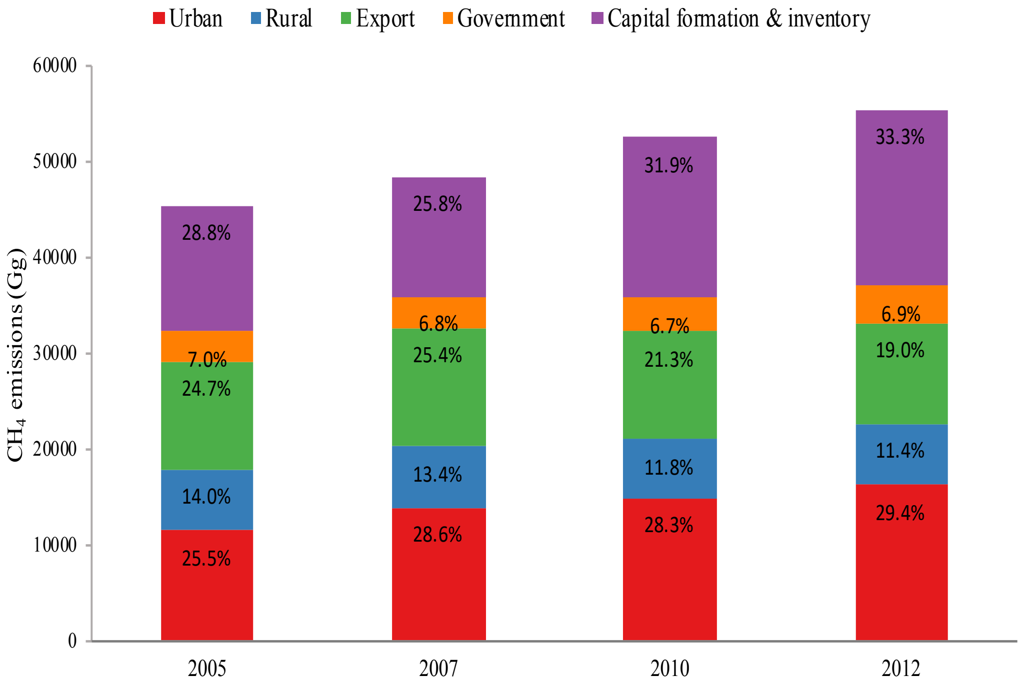


Figure 3: Embodied CH_4 emissions induced by final demand

To present more detailed descriptions on the forces behind the dynamics of embodied CH_4 emissions, we decompose them into five different final users in the perspective of consumption-based accounting, as displayed in Figure 3. The contribution of urban household consumption was increasing from 25.5% in 2005 to 29.4% in 2012, while the contribution of rural household consumption was decreasing over time. This is consistent with the urbanization process of China. From 2005 to 2012, the ratio of urban population to the total population increased 22%, and the ratio of rural population decreased 17% (NBSC, 2013). The share of CH_4 emissions induced by export also decreased after 2007. This decline can be attributed to two reasons. First, the global financial crisis sharply decreased China's export volume after 2007, hereby dragging down embodied CH_4 emissions. Second, to deal with the dramatic decline in exports, the Chinese government adjust export structure by reducing the exports of farm products and minerals, and increasing manufactured goods. This structural change leads to decrease in the embodied CH_4 emission intensity of exporting goods. Meanwhile, the contribution of capital formation increased dramatically after 2007 and became the greatest contributor hereafter, coinciding with the national economic stimulus plan during the financial crisis to maintain the economic growth. The four trillion investments were mainly made on infrastructure construction, which incurred higher demands for CH_4-intensive intermediate inputs. As for government consumption, it accounted for only 7% of CH_4 emissions and remained quite stable during the sample period.

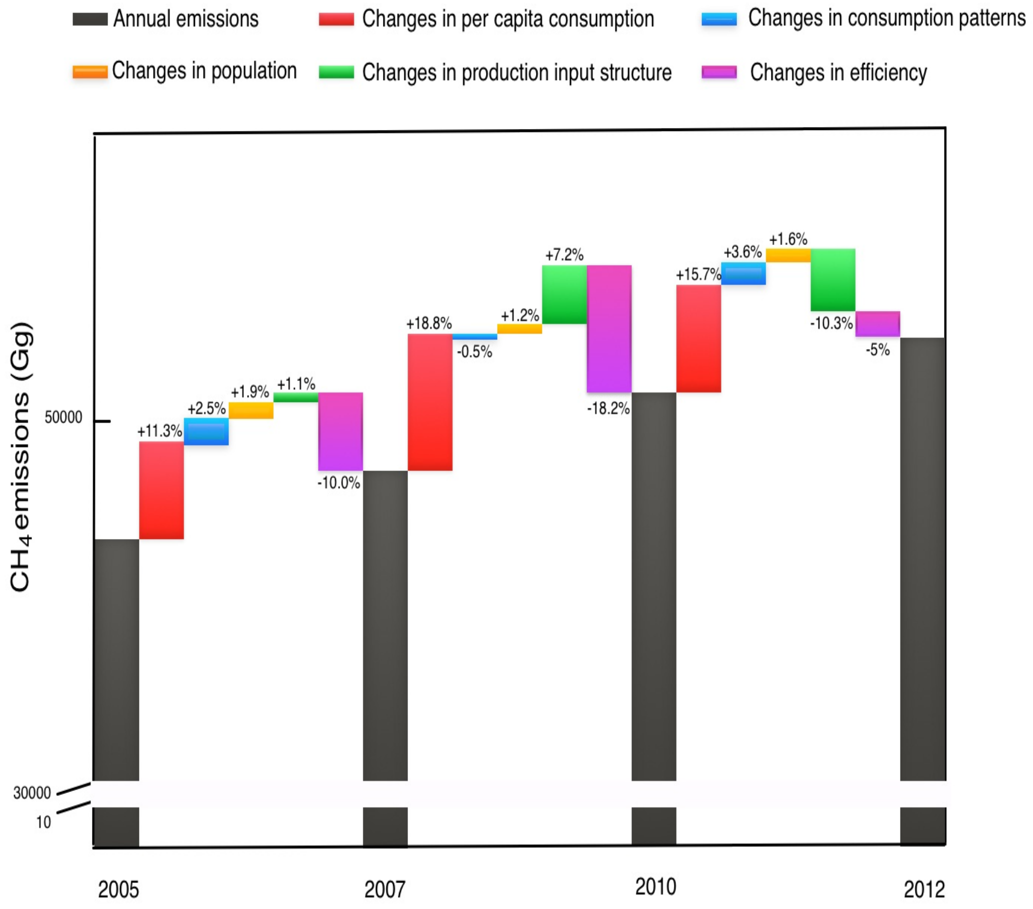
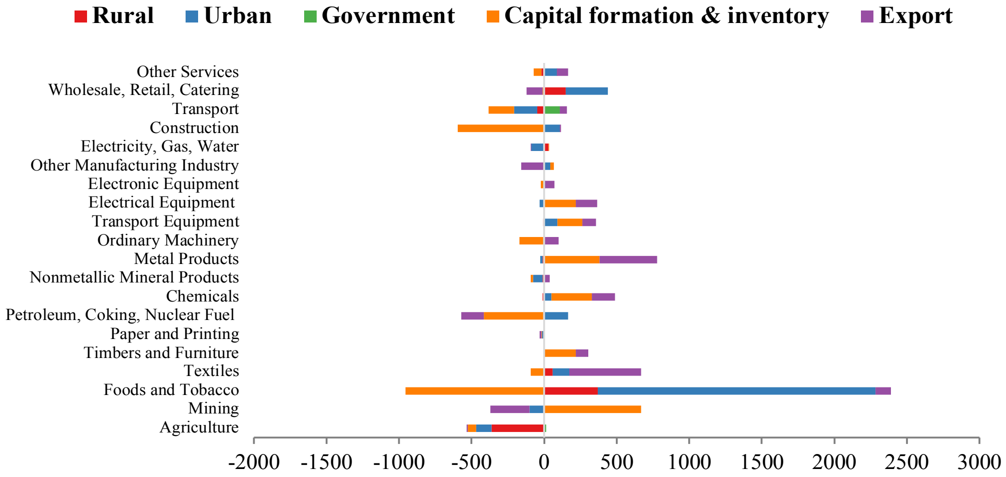


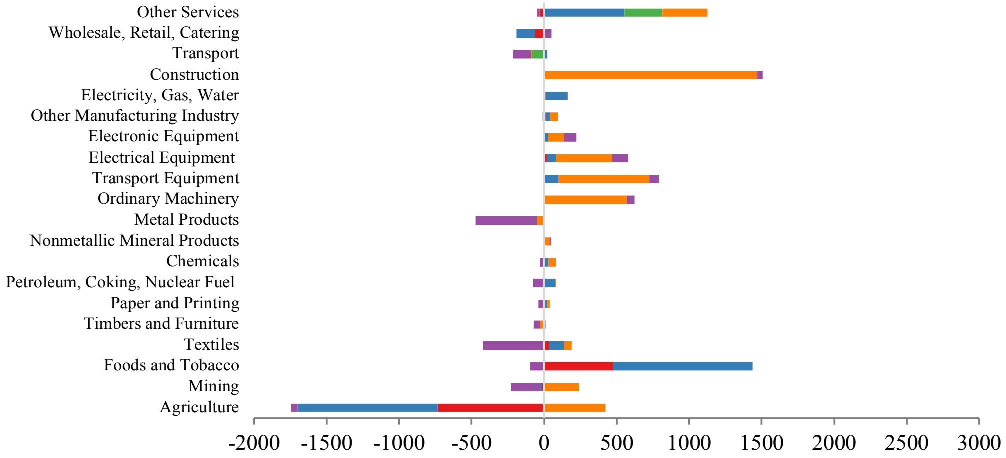
Figure 4: Fluctuations of the contributions of different factors to embodied CH_4 emissions

Although the changes in those determinants varied greatly over time, the CH_4 emissions of China kept a stable growth rate. Figure 4 displays how the changes in the five components led to the observed CH_4 emissions. Efficiency change was the major driver of offsetting CH_4 emissions, but the advantage of efficiency improvement decreased suddenly after 2010, reflecting the slowdown of productivity growth. Consistent with the economic stimulus plan of expanding domestic demand, the growth rate of CH_4 emissions induced by per capita consumption reach its peak in 2010 and then decreased marginally. A startling change was the contribution of production input structure after 2010. It remained increasing until that time but suddenly jumped to negative. As aforementioned, this was the result of economic restructuring. The growth rates of the contribution from consumption patterns experienced ups and downs as well but at a more moderate rate.

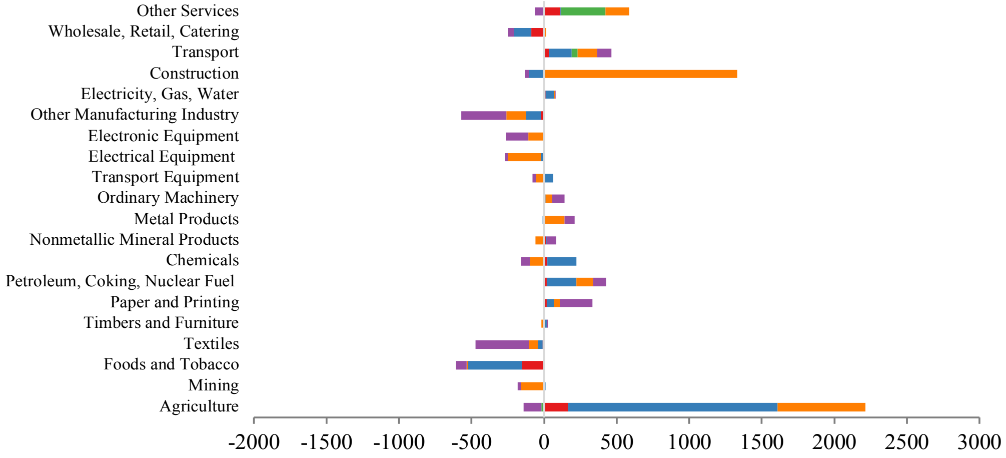
Employing structural decomposition, we next examine CH_4 emission changes by sectors in the perspective of consumption. As presented in Figure 5, the Agriculture sector experienced notable changes: its consumption-based emissions witnessed a steady decline during 2005-2010 which decreased from 9950 Gg in 2005 to 8110 Gg in 2010, followed by a sharp increase to 10180 Gg in 2012. The sharp decrease during 2007-2010 was mainly driven by the declines of urban and rural consumption, due to the global financial crisis and economic downturn, while the considerable increase during 2010-2012 could be attributed to the reform of income distribution which promoted urban and rural consumption. For most manufacturing sectors, capital formation was the major driver of embodied emission changes before 2010. Capital formation actually significantly drove up almost all sectors' emissions from 2007 to 2010. This coincides with the economic stimulus plan that focused on fixed-asset investments and infrastructure. However, after 2010, the contribution from capital formation became much smaller, except for the Construction sector whose products are counted as fixed assets. This decrease again reflects the economic structure shifting from investment-driven economy to consumption-driven economy. Contrary to the trend of Agriculture, the embodied emissions from the Foods and tobacco sector increased significantly from 2005 to 2010, and decreased



(a) Changes from 2005 to 2007 (Gg)



(b) Changes from 2007 to 2010 (Gg)



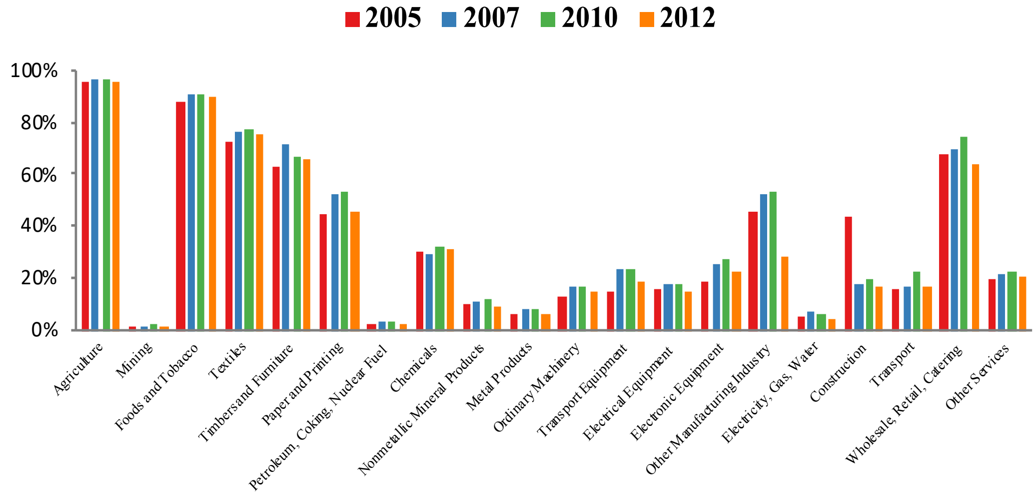
(c) Changes from 2010 to 2012 (Gg)

Figure 5: Contributions of different sectors to embodied CH_4 emissions

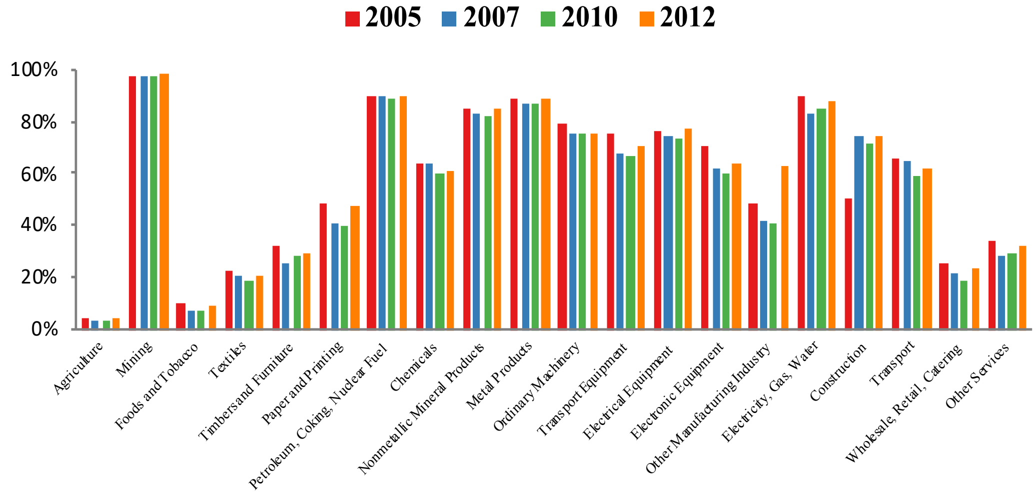
about 8% after 2010, which were mainly led by urban and rural consumption changes. The role of export is also significant. Before the financial crisis, it increased embodied emissions of China's major export sectors, e.g. Textiles, Chemicals, Metal Products and Electrical Equipment. But between 2007 and 2010, the contributions from export diminished to negative or negligible due to the sharp decline in foreign demand, and then it recovered gradually after 2010. Government consumption contributed negligible shares to all sectors except Transport and Other Services.

To better understand the role of Agriculture in the embodied CH_4 emissions, we conduct a counter-factual analysis by assigning the emission intensity of other sectors to be zero and leaving the emission intensity of Agriculture unchanged, then calculating the embodied emissions for each sector. Figure 6 presents the percentages of the fabricated emissions to actual induced emissions. More than 95% of Agriculture's CH_4 emissions came from itself, and about 90% of Foods and tobacco's emissions also came from Agriculture. CH_4 emissions induced from the final demand towards Textiles, Timbers and Furniture, and Paper and Printing were mainly attributed to Agriculture as well, while it contributed little to the Mining sector's CH_4 emissions.

In contrast to the previous results of Agriculture sector, the embodied emissions induced by the Mining sector almost completely came from itself, while it contributed little to the emissions of the Agriculture sector. About 90% of the embodied emissions from Petroleum, coking, nuclear fuel, which required primary energy as intermediate inputs, could be attributed to the Mining sector. Moreover, Mining's contribution was concentrated on the heavy industries such as Metal Products, Monmetallic Mineral Products, Ordinary Machinery, Transport Equipment, Electrical Equipment, and Electronic Equipment. Most of the embodied emissions from Construction and Transport also came from Mining. These sectors consumed large amounts of energy and industrial raw materials which could be ultimately attributed to the resource extraction of the Mining sector and were consequently energy-related CH_4-intensive inputs.



(a) Agriculture



(b) Mining

Figure 6: Counter factual analysis on the contribution of Agriculture and Mining to embodied CH_4 emissions of 17 sectors

3.3 Structural changes in income-based CH_4 emissions

From the income-based perspective, Figure 7 shows how the five determinants evolved from 2005 to 2012. Per capita income was the greatest driver of emission changes and shared the same trend as per capita consumption in Figure 2 due to the positive correlation between income levels and consumption. The changes in efficiency also remained the largest counterpart of CH_4 emissions. The contribution from production output structure fluctuated in a similar trend but at a more moderate rate compared with the production input structure in Figure 2, implying production input structure changed at a greater extent than production output structure. The change in input structure was another non-negligible contributor, which kept increasing up to 10% in 2010 then decreased to 5% in 2012. This reflects the transformation on economic structure towards more balanced and sustainable developing mode. Moreover, the contribution of input structure was significantly larger than production output structure, implying how inputs are organized plays a more fundamental role in reducing enabled CH_4 emissions.

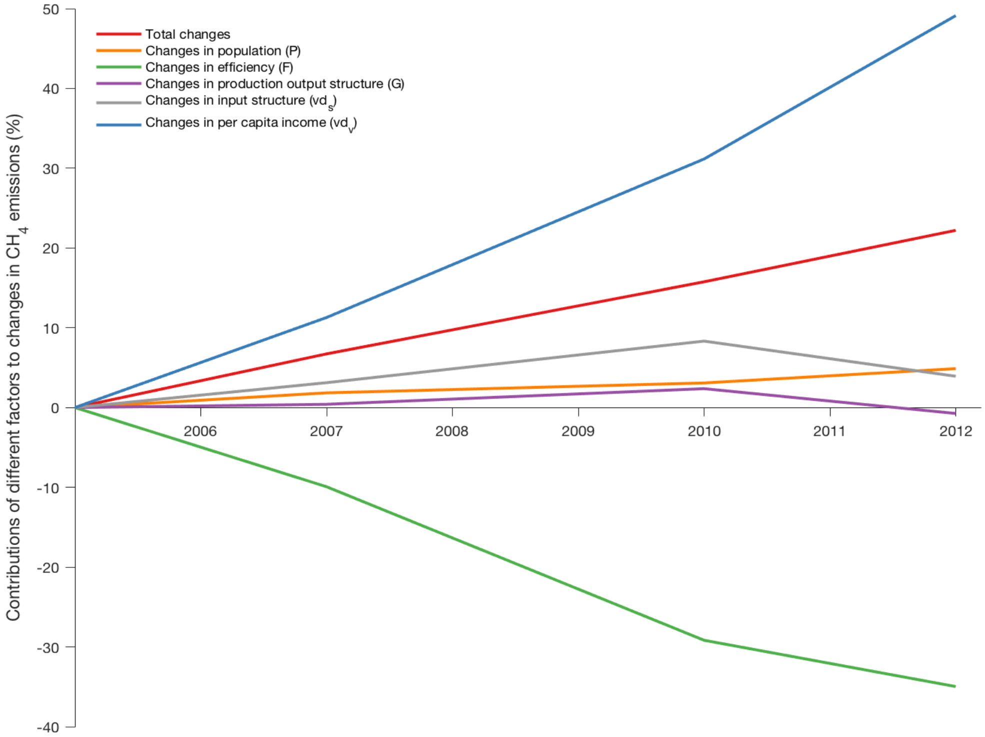


Figure 7: Contributions of different factors to changes in enabled CH_4 emissions

Later on, we decompose the enabled CH_4 emissions into four different income-components, as shown in Figure 8. Employee compensation was the major contributor of enabled CH_4 emissions all the time, and its contribution was increasing steadily from 53% to 62%. The contribution of net operating surplus continued decreasing from 25% to 17%. This phenomenon actually coincided with the national reform on income distribution system, which

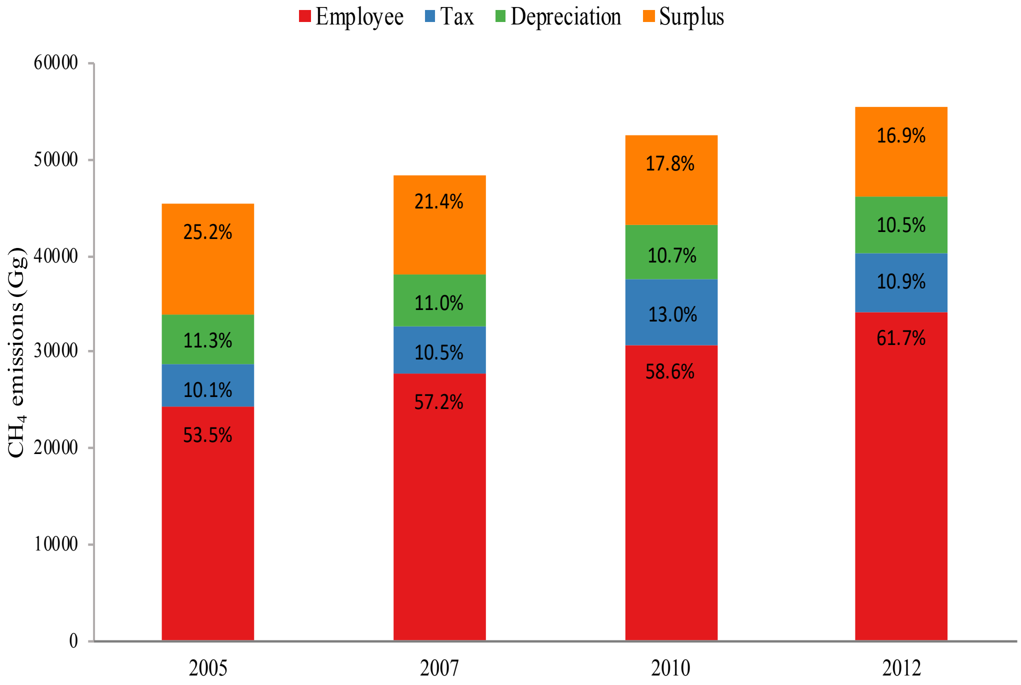


Figure 8: Enabled CH_4 emissions induced by primary inputs

increased the share of individual income in the distribution of national income and the share of work remuneration in primary distribution[1]. Therefore, the compensation to employees witnessed a notable surge and incurred higher CH_4 emissions, while the surplus of enterprises experienced a significant decrease and contributed less to the aggregate CH_4 emissions. As for the other two components, the contributions of net taxes on production and depreciation of fixed assets remained quite stable (around 11%) for all years.

Figure 9 describes how the determinants from structural decomposition led to the fluctuations of enabled CH_4 emissions from 2005 to 2012. The changes in per capita income, efficiency and population shared the same trend as Figure 5. Input structure became a major driver next to per capita income and efficiency, with the role of production output structure being more trivial. This was inherently consistent with the concept of income-based accounting because income-based emissions reflected the enabled emissions in primary

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[1] According to the official report from National Bureau of Statistics of China, the share of household income to national income increased 3% from 2009 to 2012, while the share of enterprise surplus decreased 3.9%: http://www.stats.gov.cn/tjzs/tjsj/tjcb/dysj/201511/t20151112_1273538.html.

inputs.

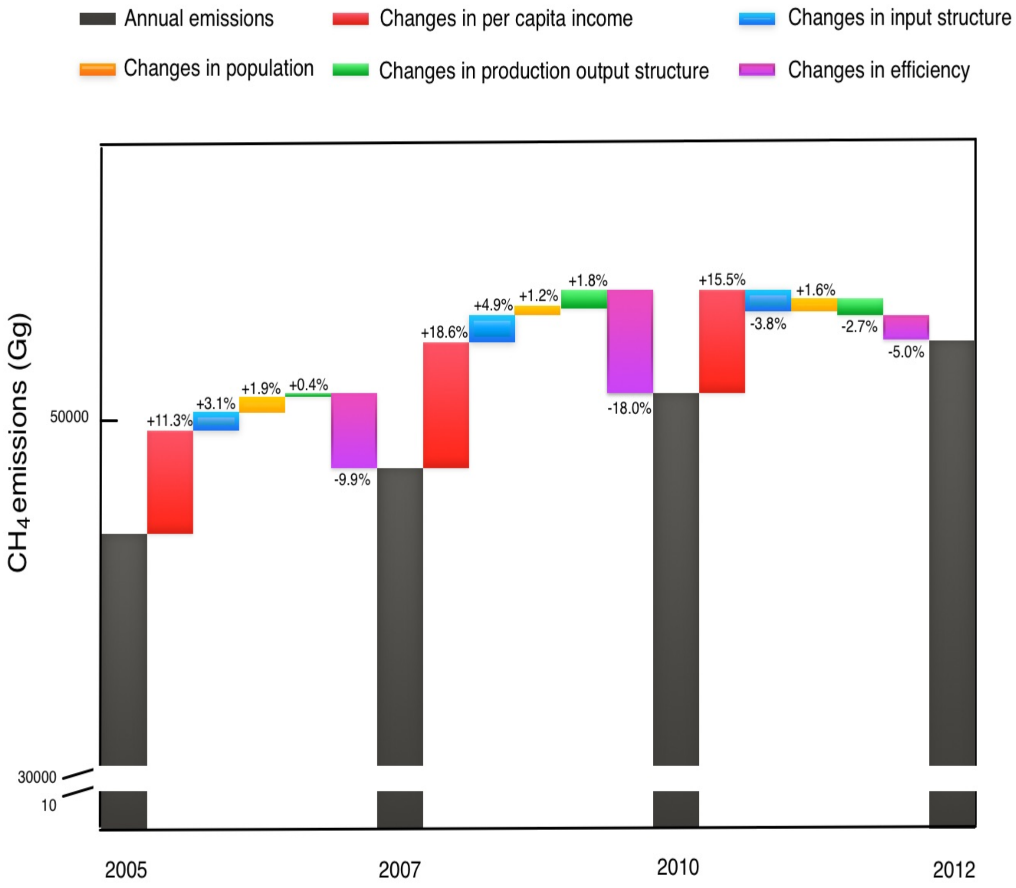


Figure 9: Fluctuations of the contributions of different factors to enabled CH_4 emissions

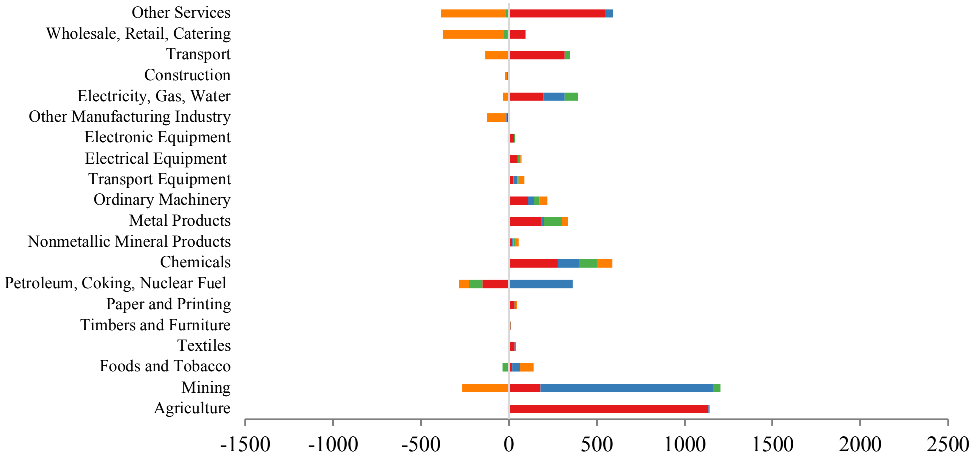
For the enabled emissions at sector level, Figure 10 shows Mining and Agriculture were the two sectors that experienced the largest increase in enabled CH_4 emissions from 2005 to 2012. In the Agriculture sector, the increase was driven by employee compensation all the time. But for the Mining sector, although employee compensation remained the greatest driver during the periods from 2005 to 2007 and from 2010 to 2012, net taxes on production surpassed wage compensation from 2007 to 2010. Furthermore, production taxes generally played a minor role except for years from 2007 to 2010, during which tax incentives were used to help enterprises live through economic downturn. Those tax incentives consequently led to production expansion and more enabled emissions. Another interesting fact on production tax is for the Agriculture sector, whose production taxes almost completely offset the emission increase incurred by employee compensation from 2010 to 2012. While employee compensation was the major driver of enabled CH_4 emissions, net operating surplus offset a large proportion of the enabled emissions from 2007 to 2010, but this offsetting effect almost disappeared during the period of 2010-2012. Depreciation of fixed assets accounted little for the enabled emissions in all sectors except Chemicals, Metal products, Utilities and Mining, which demand a large quantity of fixed assets to initiate production.

Similar to the analysis on consumption-based emissions, we conduct counter-factual decompositions for Agriculture and Mining and present the results in Figure 11. Again, more than 90% of Agriculture, Foods and Tobacco's enabled emissions came from the Agriculture sector itself, but it contributed much less to the emissions from Textiles, and Timbers and Furniture compared with Figure 6. This suggests that the two sectors used CH_4-intensive goods as intermediate inputs from Agriculture not to manufacture intermediate commodities for other sectors, but to produce final products for consumers. Moreover, in the sector of Chemicals, Agriculture explained much more enabled emissions than embodied emissions, indicating the intermediate goods supplied by Chemicals were made by the CH_4-intensive inputs from Agriculture. As for the role of Mining, besides itself, it also contributed a significant magnitude to most manufacturing sectors, suggesting its importance as intermediate input for those sectors.

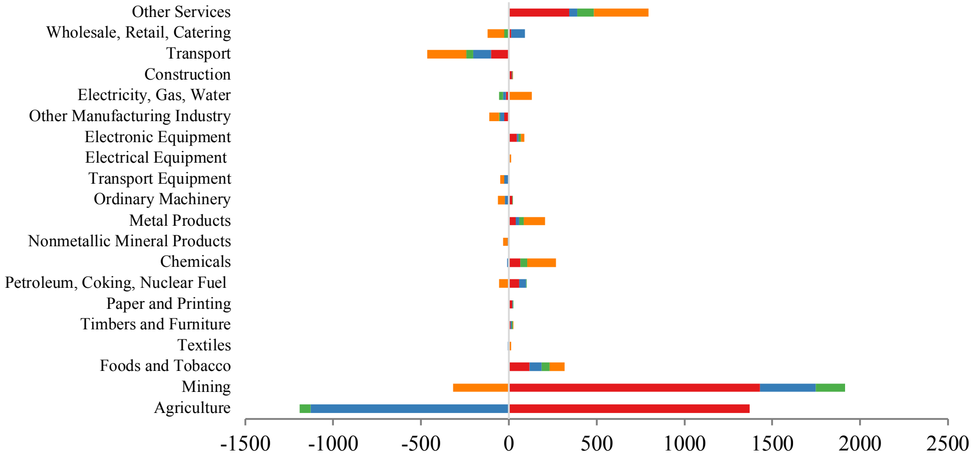
4 Discussions

China's CH_4 emission has been maintaining a steady growth rate over the last decade, its determinants, however, were profoundly affected by the global financial crisis and national economic policies. The changes in per capita consumption/income and the changes in efficiency together shaped the trend of CH_4 emissions. Due to the rapid economic development and the reform on income allocation, household income as well as consumption witnessed

(a) Changes from 2005 to 2007 (Gg)

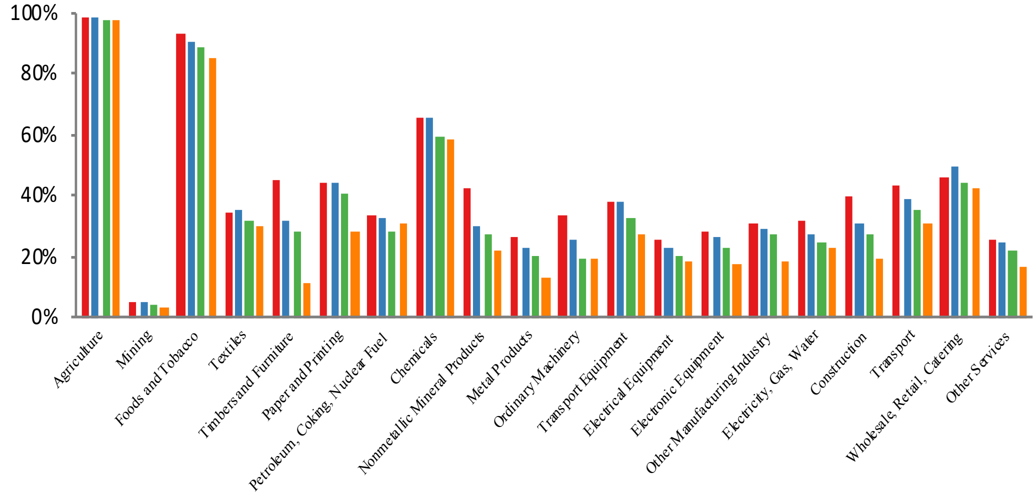


(b) Changes from 2007 to 2010 (Gg)

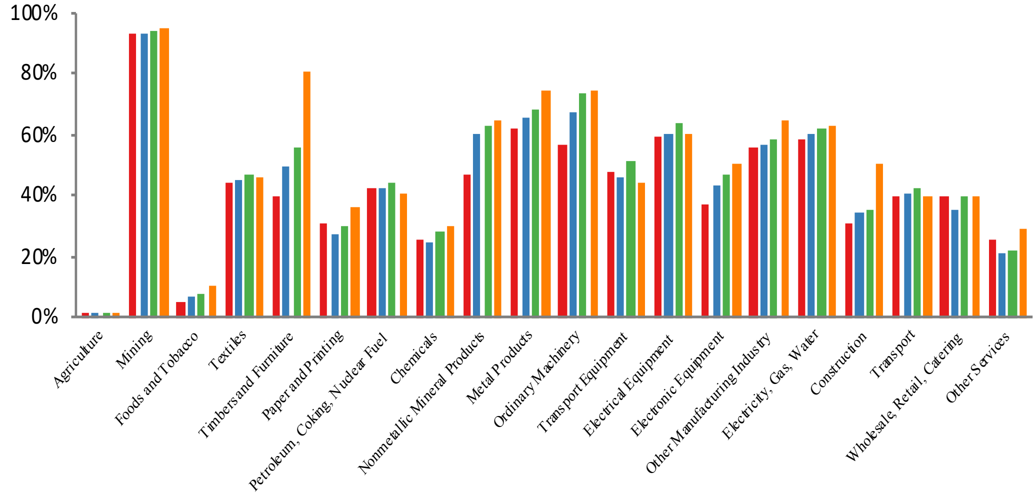


(c) Changes from 2010 to 2012 (Gg)

Figure 10: Contributions of different sectors to enabled CH_4 emissions



(a) Agriculture



(b) Mining

Figure 11: Counter factual analysis on the contribution of Agriculture and Mining to enabled CH_4 emissions of 17 sectors

sharp increases, pushing up CH_4 emissions, which was also reflected in the contributions of employee compensation and enterprise surplus to aggregate CH_4 emissions. This surge in income and consumption could impose practical limits on the reduction of emissions as long as the growing trend continues. Furthermore, with Agriculture being the largest contributor to CH_4 emissions, income growth generally shifts the structure of food consumption towards more CH_4-intensive agricultural products (e.g., meat and diary). This inevitably imposed further threats on CH_4 emission reduction. Meanwhile, efficiency change overall offset 60% of the emission increases induced by per capita consumption/income, implying the improvement in technology and productivity significantly reduced CH_4 intensity. However, the contribution of efficiency declined a large magnitude after 2010. This poses another potential threat on emission reduction because the advantages of efficiency improvement might have been well exploited and little room was left for further improvement on the basis of current technology.

Besides consumption and income, the contribution of export and capital formation also witnessed dramatic changes. Affected by external shocks of the global financial crisis, CH_4 emissions induced by export decreased after 2007, due to both the decline in external demand and the adjustment of export structure that lowered the export shares of farm products and minerals. Contrary to the trend of export, the CH_4 emissions induced by capital formation experienced a dramatical surge after 2007, coinciding with the four-trillion economic stimulus plan during the financial crisis. Those structural changes imply that the focus of controlling CH_4 emissions should be laid on the investment in construction and infrastructure instead of export.

Next we compare the determinants in our decomposition with related literature. Table 1 summarizes some literature that applies structural decomposition analysis to energy use and environmental emissions of China. In line with most existing studies, our findings emphasize the importance of consumption on CH_4 emissions. Meanwhile, efficiency change is found to be the major inhibitory factor in nearly all related literature, even in the studies of other countries and regions like the United States (De Nooij et al., 2003), Japan (Kagawa and Inamura, 2004) and Taiwan (Lee and Lin, 2001). Similar to the research on CO_2 emissions (e.g. Feng et al., 2012; Mi et al., 2017a,b; Wang and Feng, 2017), our decomposition results imply that population had a minor effect on CH_4 emissions. Capital formation and exports, as the dominant driver of China's CO_2 emissions (Feng et al., 2017) and energy demand (Xu et al., 2014; Wu and Zhang, 2016), also contributed significant shares to China's CH_4 emissions.

Table 1: SDA studies on China's environmental emissions and energy use

Publication	Indicator	Sample period	Method
Guan et al., 2008	CO_2 emissions	1980-2030	Consumption-based SDA
Guan et al., 2009	CO_2 emissions	2002-2005	Consumption-based SDA
Zhang, 2009	CO_2 emissions	1992-2006	Consumption-based SDA
Xu et al., 2011	CO_2 emissions	2002-2008	Consumption-based SDA
Guan et al., 2014	$PM_{2.5}$	1997-2010	Consumption-based SDA
Xie, 2014	Energy use	1992-2010	Consumption-based SDA
Wu and Zhang, 2016	Energy use	1997-2012	Consumption-based SDA
Yuan and Zhao, 2016	CO_2 emissions	2005 and 2010	Consumption- and income-based SDA
Feng et al., 2017	CO_2 emissions	1995-2009	Consumption- and income-based SDA
Liu and Liang, 2017	Pollutants	2007-2012	Consumption-based SDA
Mi et al., 2017a	CO_2 emissions	2005-2012	Consumption-based SDA
Su and Ang, 2017	CO_2 emissions	2007-2012	Consumption-based SDA
Wang and Feng, 2017	CO_2 emissions	2000-2014	Income-based SDA
Zhao et al., 2017	CO_2 emissions	1992-2012	Income-based SDA
Zhang et al., 2018b	Mercury	1997-2012	Consumption- and income-based SDA

The shocks of the global financial crisis on GHG emissions are also detected by other researchers. Feng et al. (2015) found that the co-movements between CO_2 emissions and economic growth in the US, i.e. emissions before 2007 were risen by economic growth, and were decreased by the economic recession after 2007. Consistent with our findings on the contribution changes of export and capital formation to total emissions, Mi et al. (2017a) reported that CO_2 emissions induced by export declined while the emissions induced by capital formation surged upwards. Moreover, as we demonstrate that changes in production and input structure after 2010 decreased CH_4 emissions, they also found structural upgrading significantly offset CO_2 emissions. But contrary to the shift towards consumption-driven economy, at the aggregate level, the contribution of capital formation to CH_4 emissions has been increasing and it has become the greatest contributor since 2010. The importance of capital formation has also been noticed by the studies on energy consumption and pollutants emissions. Guan et al. (2014) and Deng et al. (2016) found that capital formation was the largest final demand category for increasing air pollutants, most of which were embodied in the construction sector. Energy-related CH_4 emissions account for a significant share of China's CH_4 emissions, while CO_2 emissions are mainly attributed to the energy consumption. Joint efforts and coordinated control should be taken on CH_4 and other environmental emissions.

5 Concluding remarks

Reducing global emissions of CO_2, CH_4 and other greenhouse gases is a major challenge. The significant amount and sustained growth of anthropogenic CH_4 emissions in China has greatly affected the country's own efforts to mitigate GHG emissions. In combination with EEIOA and SDA methods, this paper employs both consumption- and income-based accounting technologies to clarify the socioeconomic determinants of China's CH_4 emissions from a systemic perspective. In contrast to production- and income-based emissions mainly from the Agriculture and Mining sectors, the Manufacturing, Construction and Service sectors accounted for a large magnitude of consumption-based emissions. Changes in per capita consumption/income and efficiency improvement collectively shaped the trend of CH_4 emissions, with per capita consumption and income proving to be the greatest driving forces. While changes in efficiency offset a significant amount of emission increases, its contribution plunged after 2010. Capital formation- and exports-driven CH_4 emissions surged and declined separately after 2007. The relevant components of final demand and primary inputs fluctuated dramatically, but capital formation and employee compensation remained as major determinants of embodied and enabled emissions respectively. China's growing CH_4 emissions were found to be profoundly affected by the global financial crisis of 2007, as well as its economic stimulus plan and the income distribution reform implemented there after. These findings provide additional insights for policy makers on the mitigation of CH_4 and other emissions. Declining contribution from technology reinforces the unheeded warning that the efficiency changes might have limited mitigation potential, and that relying on technology improvement alone is insufficient to achieve mitigation goals. Moreover, growing household income and consumption further doubts on the country's ability to reducing CH_4 emissions. With the Chinese economy entering into a "new normal", adjusting the consumption and supply structures could be more effective in mitigating CH_4. Since China still lacks a comprehensive plan for CH_4 emissions reduction, examining both consumption-based and income-based emissions will be useful for understanding the drivers of China's anthropogenic CH_4 emissions and thus for crafting appropriate mitigation policies and actions covering the entire supply chains.

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References

Arto, I. Dietzenbacher, E., 2014. Drivers of the growth in global greenhouse gas emissions. Environmental Science & Technology, 48(10), 5388-5394.

Chen, G.Q. Zhang, B., 2010. Greenhouse gas emissions in China 2007: inventory inputoutput analysis. Energy Policy, 38(10), 6180-6193.

Climate Change Department of National Development Reform Commission (CCDNDRC) (2017), The People's Republic of China First Biennial Update Report on Climate Change, CCDNDRC, Beijing, China.http://www.ccchina.gov.cn/archiver/ccchinacn/UpFile/Files/Default/20170124155928346053.pdf.

De Nooij, M., van der Kruk, R., Van Soest, D.P., 2003. International comparisons of domestic energy consumption. Energy Economics, 25(4), 359-373.

Deng, G., Ding, Y. Ren, S., 2016. The study on the air pollutants enabled in goods for consumption trade in China-Accounting structural decomposition analysis. Journal of Cleaner Production, 135, 332-341.

Deng, G. Xu, Y., 2017. Accounting structure decomposition analysis of enabled carbon trade: A global perspective. Energy, 137, 140-151.

Dietzenbacher, E., Los, B., 1998. Structural decomposition techniques: sense and sensitivity. Economic Systems Research, 10(4), 307-324.

Du, G., Sun, C., Ouyang, X., Zhang, C., 2018a. A decomposition analysis of energy-related CO_2 emissions in Chinese six high-energy intensive industries. Journal of Cleaner Production 184, 1102-1112.

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.

Du, M., Zhu, Q., Wang, X., Li, P., Yang, B., Chen, H., Wang, M., Zhou, X. Peng, C., 2018b. Estimates and predictions of methane emissions from wastewater in China from 2000 to 2020. Earth's Future, 6(2), 252-263.

EDGAR, Emission Database for Global Atmospheric Research (EDGAR), 2017. Release version 4.3. European Commission, Joint Research Centre (JRC)/ PBL Netherlands Environmental Assessment Agency. http://edgar.jrc.ec.europe.eu/index.php/.

Feng, K., Siu, Y.L., Guan, D. Hubacek, K., 2012. Analyzing drivers of regional carbon dioxide emissions for China. Journal of Industrial Ecology, 16(4), 600-611.

Feng, K., Davis, S.J., Sun, L., Hubacek, K., 2015. Drivers of the US CO_2 emissions 1997-2013. Nature communications, 6, 7714.

Feng, T.T., Yang, Y.S., Xie, S.Y., Dong, J. Ding, L., 2017. Economic drivers of greenhouse gas emissions in China. Renewable and Sustainable Energy Reviews, 78, 996-1006.

Ghosh, A., Patra, P.K., Ishijima, K., Umezawa, T., Ito, A., Etheridge, D.M., Sugawara, S., Kawamura, K., Miller, J.B., Dlugokencky, E.J. and Krummel, P.B., 2015. Variations in global methane sources and sinks during 1910-2010. Atmospheric Chemistry and Physics, 15(5), 2595-2612.

Guan, D., Hubacek, K., Weber, C.L., Peters, G.P. Reiner, D.M., 2008. The drivers of Chinese CO_2 emissions from 1980 to 2030. Global Environmental Change, 18(4), 626-634.

Guan, D., Peters, G. P., Weber, C. L. Hubacek, K., 2009. Journey to world top emitter: An analysis of the driving forces of China's recent CO_2 emissions surge. Geophysical Research Letters, 36(4).

Guan, D., Su, X., Zhang, Q., Peters, G. P., Liu, Z., Lei, Y. He, K., 2014. The socioeconomic drivers of China's primary PM_2.5 emissions. Environmental Research Letters, 9(2), 024010.

Hawkins, J., Ma, C., Schilizzi, S., Zhang, F., 2015. Promises pitfalls in environmentally extended input-output analysis for China: A survey of the literature. Energy Economics, 48, 81-88.

Hoekstra, R., Van Den Bergh, J. C., 2002. Structural decomposition analysis of physical flows in the economy. Environmental and Resource Economics, 23(3), 357-378.

Intergovernmental Panel on Climate Change (IPCC), 2014, IPCC fifth assessment report: climate change 2013 (AR5), IPCC, Cambridge, N. Y. (http://www.ipcc.ch/index.htm/)

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Bergamaschi, P., Pagliari, V., Olivier, J.G.J., Peters, J.A.H.W., van Aardenne, J.A., Monni, S., Doering, U., Petrescu, A.M.R., 2017. EDGAR v4.3.2 Global Atlas of the three major Greenhouse Gas Emissions for the period 1970-2012, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2017-79, in review.

Jiao, J., Han, X., Li, F., Bai, Y., Yu, Y., 2017. Contribution of demand shifts to industrial SO_2 emissions in a transition economy: Evidence from China. Journal of Cleaner Production, 164, 1455-1466.

Kagawa, S., Inamura, H., 2004. A spatial structural decomposition analysis of Chinese and Japanese energy demand: 1985-1990. Economic Systems Research, 16(3), 279-299.

Lee, C.F., Lin, S.J., 2001. Structural decomposition of CO_2 emissions from Taiwan's petrochemical industries. Energy Policy, 29(3), 237-244.

Liang, S., Qu, S., Zhu, Z., Guan, D., Xu, M., 2016a. Income-based greenhouse gas emissions of nations. Environmental Science and Technology, 51(1), 346-355.

Liang, S., Wang, H., Qu, S., Feng, T., Guan, D., Fang, H., Xu, M., 2016b. Socioeconomic drivers of greenhouse gas emissions in the United States. Environmental Science and Technology, 50(14), 7535-7545.

Li, B., T. Gasser, P. Ciais, S. Piao, S. Tao, Y. Balkanski, et al, 2016. The contribution of China's emissions to global climate forcing. Nature, 531(7594), 357-361.

Liu, H., Fan, X., 2017. Value-added-based accounting of CO_2 emissions: A multi-regional input-output approach. Sustainability, 9(12), 2220.

Liu, H., Xi, Y., Guo, J. E. Li, X., 2010. Energy enabled in the international trade of China: an energy input-output analysis. Energy Policy, 38(8), 3957-3964.

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, 76-86.

Malik, A., Lan, J., Lenzen, M., 2016. Trends in global greenhouse gas emissions from 1990 to 2010. Environmental Science and Technology, 50 (9), 4722-4730.

Marques, A., Rodrigues, J., Domingos, T., 2013. International trade and the geographical separation between income and enabled carbon emissions. Ecological Economics, 89, 62-169.

Mi, Z., Meng, J., Guan, D., Shan, Y., Liu, Z., Wang, Y., Feng, K. Wei, Y. M., 2017a. Pattern changes in determinants of Chinese emissions. Environmental Research Letters, 12(7), 074003.

Mi, Z., Wei, Y.M., Wang, B., Meng, J., Liu, Z., Shan, Y., Liu J., Guan D., 2017b. Socioeconomic impact assessment of China's CO_2 emissions peak prior to 2030. Journal of Cleaner Production 142(4), 2227-2236.

Miller, R.E., Blair, P.D., 2009. Input-output analysis: foundations and extensions. Cambridge University Press.

Montzka, S. A., Dlugokencky, E. J.,Butler, J. H., 2011. Non-CO_2 greenhouse gases and climate change. Nature, 476(7358), 43-50.

NBSC, National Bureau of Statistics of China, 2013. China Statistical Yearbook 2013. Also available at: http://www.stats.gov.cn/tjsj/ndsj/2013.

Nisbet, E.G., Dlugokencky, E.J., Manning, M.R., Lowry, D., Fisher, R.E., France, J.L., Michel, S.E., Miller, J.B., White, J.W.C., Vaughn, B., Bousquet, P., Pyle, J.A., Warwick, N.J., Cain, M., Brownlow, R., Zazzeri, G., Lanoisell, M., Manning, A.C., Gloor, E., Worthy, D.E.J., Brunke, E.G., Labuschague, C., Wolff, E.W., Ganesan, A.L., 2016. Rising atmospheric methane: 2007-2014 growth isotopic shift. Global Biogeochem Cycles, 30, 1356-1370.

Peng, S., Piao, S.,Bousquet, P., Ciais, P., Li, B., Lin, X., Tao, S., Wang, Z., Zhang, Y., Zhou, F., 2016. Inventory of anthropogenic methane emissions in Mainland China from 1980 to 2010. Atmospheric Chemistry and Physics, 16(22), 14545-14562.

Peters, G. P., Weber, C. L., Guan, D. Hubacek, K., 2007. China's growing CO_2 emissions–a race between increasing consumption and efficiency gains. Environmental Science & Technology, 41(17), 5939-5944.

Saunois, M., Jackson, R.B., Bousquet, P., Poulter, B., Canadell, J.G., 2016. The growing role of methane in anthropogenic climate change. Environmental Research Letters, 11 (12), 120207.

Schaefer, H., Fletcher, S. E. M., Veidt, C., Lassey, K. R., Brailsford, G. W., Bromley, T. M., Dlugokencky, E. J., Michel, S. E., Miller, J. B., Levin, I., Lowe, D. C., Martin, R. J., Vaughn, B. H., White, J. W.

C., 2016. A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by CH_4. Science, 352(6281), 80-84.

Shi, Q., Chen, J., Shen, L., 2017. Driving factors of the changes in the carbon emissions in the Chinese construction industry. Journal of Cleaner Production, 166, 615-627.

Su, B., Ang, B. W., 2012. Structural decomposition analysis applied to energy emissions: some methodological developments. Energy Economics, 34(1), 177-188.

Su, B., Ang, B. W., 2017. Multiplicative structural decomposition analysis of aggregate enabled energy emission intensities. Energy Economics, 65, 137-147.

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.

Turner, A. J., Frankenberg, C., Wennberg, P. O., Jacob, D. J., 2017. Ambiguity in the causes for decadal trends in atmospheric methane and hydroxyl. Proceedings of the National Academy of Sciences, 201616020.

United States Environmental Protection Agency (USEPA), 2012, EPA report 430-R-12-006, global anthropogenic non-CO_2 GHG emissions: 1990-2030. (http://www.epa.gov/climatechange/Downloads/EPAactivities/EPA_Global_NonCO2_Projections_Dec2012.pdf)

Wang, H., Ang, B.W., Su, B., 2017a. Assessing drivers of economy-wide energy use emissions: IDA versus SDA. Energy Policy, 107, 585-599.

Wang, M., Feng, C., 2017. Decomposition of energy-related CO_2 emissions in China: An empirical analysis based on provincial panel data of three sectors. Applied Energy, 190, 772-787.

Wang, L., Xue, B., Yan, T., 2017b. Greenhouse gas emissions from pig and poultry production sectors in China from 1960 to 2010. Journal of Integrative Agriculture, 16(1), 221-228.

Wei, J., Huang, K., Yang, S., Li, Y., Hu, T., Zhang, Y., 2017. Driving forces analysis of energy-related carbon dioxide (CO_2) emissions in Beijing: an input-output structural decomposition analysis. Journal of Cleaner Production, 163, 58-68.

Wu, X.F.,Chen, G.Q., 2017. Energy use by Chinese economy: A systems cross-scale input-output analysis. Energy Policy, 108, 81-90.

Wu, Y., Zhang, W., 2016. The driving factors behind coal demand in China from 1997 to 2012: An empirical study of input-output structural decomposition analysis. Energy Policy, 95, 126-134.

Xie, S. C., 2014. The driving forces of China's energy use from 1992 to 2010: An empirical study of input-output structural decomposition analysis. Energy Policy, 73, 401-415.

Xu, M., Li, R., Crittenden, J. C., Chen, Y., 2011. CO_2 emissions enabled in China's exports from 2002 to 2008: a structural decomposition analysis. Energy Policy, 39(11), 7381-7388.

Xu, S.C., He, Z.X., Long, R.Y., 2014. Factors that influence carbon emissions due to energy consumption in China: Decomposition analysis using LMDI. Applied Energy, 127, 182-193.

Yang, R., Zhu, T., Gao, Q., 2014. Technologies policy recommendations for emission reduction of non-CO_2 greenhouse gas from typical industries in China. China Environmental Science Press, Beijing, China.

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. http://www.wri.org/sites/default/files/Opportunities_to_enhance_non-CO2_GHG_mitigation_in_China.pdf.

Yuan, R., Zhao, T., 2016. Changes in CO_2 emissions from China's energy-intensive industries: a subsystem input-output decomposition analysis. Journal of Cleaner Production, 117, 98-109.

Yuan, R., Behrens, P., Rodrigues, J. F., 2018. The evolution of inter-sectoral linkages in China's energy-related CO_2 emissions from 1997 to 2012. Energy Economics, 69, 404-417.

Zeng, L., Xu, M., Liang, S., Zeng, S., Zhang, T., 2014. Revisiting drivers of energy intensity in China during 1997-2007: A structural decomposition analysis. Energy Policy, 67, 640-647.

Zhang, B. Methane emissions in China: Time series inventories and systems embodiment analysis, Ph.D. Dissertation; Peking University, Beijing, 2011 (in Chinese).

Zhang, B., Chen, G., 2010, Methane emissions by Chinese economy: Inventory embodiment analysis. Energy Policy, 38(8), 4304-4316.

Zhang, B., Chen, G., 2014, Methane emissions in China 2007. Renewable & Sustainable Energy Reviews, 30, 886-902.

Zhang, B., Chen, G., Li, J., Tao, L., 2014, Methane emissions of energy activities in China 1980-2007. Renewable and Sustainable Energy Reviews, 29(7), 11-21.

Zhang, B., Chen, Z., Qiao, H.,Chen, B., Hayat, T., Alsaedi, A., 2015, China's non-CO_2 greenhouse gas emissions: Inventory input-output analysis. Ecological Informatics, 26(10), 101-110.

Zhang, B., Zhang, Y., Zhao, X., Meng, J., 2018a. Non-CO_2 greenhouse gas emissions in China 2012: Inventory and supply chain analysis. Earth's Future, 6, 103-116.

Zhang, H., Chen, L., Tong, Y., Zhang, W., Yang, W., Liu, M., Liu, L., Wang, H., Wang, X., 2018b. Impacts of supply and consumption structure on the mercury emission in China: An input-output analysis based assessment. Journal of Cleaner Production, 170, 96-107.

Zhang, H., Qi, Y., 2011. A structure decomposition analysis of China's production-source CO_2 emission: 1992-2002. Environmental and Resource Economics, 49(1), 65-77.

Zhang, Y., 2009. Structural decomposition analysis of sources of decarbonizing economic development in China; 1992-2006. Ecological Economics, 68(8-9), 2399-2405.

Zhang, Y., 2010. Supply-side structural effect on carbon emissions in China. Energy Economics, 32(1), 186-193.

Zhao, X., Zhang, X., Li, N., Shao, S. Geng, Y., 2017. Decoupling economic growth from carbon dioxide emissions in China: A sectoral factor decomposition analysis. Journal of Cleaner Production, 142, 3500-3516.

Zhou, C., Wang, S., Feng, K., 2018. Examining the socioeconomic determinants of CO_2 emissions in China: A historical prospective analysis. Resources, Conservation and Recycling, 130, 1-11.

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