Carbon implications of China's changing economic structure at the city level

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Abstract: Carbon emissions are strongly related to economic development. China has entered a new phase of economic development – "New Normal" – in which large-scale and multidimensional changes are occurring in the economic structure. This study aims to estimate the carbon implications of these changes in the economic structure at the city level. We compiled a multiregional input-output (MRIO) model for China and used an environmentally extended input-output analysis (EEIOA) to estimate CO_2 emissions in Shanghai from both production and consumption perspectives. We found that consumption-based CO_2 emissions were more than 30% higher than production-based emissions in Shanghai. In recent years, both production- and consumption-based CO_2 emissions in Shanghai declined because of changes in China's economic development mode. The production-based emissions declined mainly due to changes in the production structure and energy mix, while the consumption-based emissions declined mainly due to changes in consumption patterns and domestic interregional emission flows.

Key words: Economic structure, carbon emissions, consumption patterns, input-output model

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1. Introduction

Energy-related carbon emissions are strongly related to economic development (Han et al., 2017; Zhang et al., 2017). China has enjoyed rapid economic growth over the past several decades. The growth rate of the average annual gross domestic product (GDP) exceeded 10% for a long period until the global financial crisis in 2008. The rapid economic growth was supported by high energy consumption, which generated significant greenhouse gas (GHG) emissions (Engström, 2016; Jarke and Perino, 2017). As a result, since 2006, China has become the largest CO_2 emitter in the world and has contributed more than 25% of global emissions (Liu et al., 2015; Mi et al., 2017c).

However, the global financial crisis significantly affected Chinese economic development (Long and Herrera, 2018; Overholt, 2010); the annual GDP growth rate declined from more than 14% in 2007 to less than 7% in 2016. The Chinese government introduced a large economic stimulus plan, including the domestic Four Trillion Yuan Stimulus Package, and established institutions and initiatives to expand foreign investment, including the Asian Infrastructure Investment Bank and the Belt and Road Initiatives. In recent years, China's economy has been unable to continue the double-digit economic growth of previous decades. Instead, the country has entered a "new normal" phase of socioeconomic development in which large-scale and multidimensional changes in economic structure are happening (Green and Stern, 2017; Mi et al., 2018). Specifically, China's production and consumption structure, export and import structure, urban-rural structure, interregional structure, and roles in international trade have changed under the new normal conditions (Mi et al., 2017a).

These structural changes in China's economy have major implications for energy consumption as well as carbon emissions. The Chinese government has made an international commitment to reach peak CO_2 emissions by approximately 2030. However, recent structural changes, along with increases in non-fossil energy production, have so dramatically affected coal consumption that China's carbon emissions have already started to flatten out — on some accounts, they have even been declining since 2013. Some recent studies have explored the carbon implications of China's changing economic structure at the national level. Mi et al. (2017a) used structural decomposition analysis (SDA) to estimate the impacts of the economic structural changes on the driving factors of China's CO_2 emission changes from 2005 to 2012. They found that changes in the production and consumption structure have become the strongest factor to offset China's CO_2 emissions in the new normal. Mi et al. (2017b) used the multiregional input-output (MRIO) model to estimate the impacts of changes in China's economic structure and its role in global trade on CO_2 emissions during the 2007-2012 period. The results showed that emission flow patterns have changed significantly since the global financial crisis, irrespective of domestic or foreign trade. Green and Stern (2017) tracked the recent changes in China's economy since 2000 and analysed their recent and future impacts on carbon emissions. They used the Kaya components approach to forecast that China's CO_2 emissions are likely to peak by 2025 due to structral tranformation in the country. Zhang et al. (2016) estimated the impacts of China's new policy directives on climate change outcomes in the new normal. They argued that China's CO_2 emissions will peak by approximately 2030 under China's new policies, which is different from the results of Green and Stern (2017).

However, these studies estimated national-level impacts of the changing economic structure on CO_2 emissions. To date, studies have seldom focused on the carbon implications at a city level. Therefore, a key contribution of this paper is to fill this research gap by estimating the carbon implications of China's changing economic structure in Shanghai, one of the most developed cities in eastern coastal China. It needs to be noted that Shanghai is a provincial-level city, with a population of over 24 million as of 2017. We selected Shanghai as an example for two reasons. First, Shanghai is one of the cities where economic structure changes fastest in China. Shanghai is always at the forefront of socioeconomic transformation in this country. The central government usually selects Shanghai to carry out pilot projects on economic transformation policies, such as the Shanghai Pilot Free Trade Zone. Second, Shanghai has closer economic connections with foreign countries compared to other regions in China. Due to its geographical location and government policy directives, Shanghai is well connected in international trade with a large amount of imports as well as exports. Therefore, the city is largely affected by global economic development.

In this study, we analyse the carbon emissions in Shanghai city from both consumption and production perspectives. There are two approaches to calculate carbon emissions of a region: production- and consumption-based accounting (Su and Ang, 2014, 2017). Under production-based accounting, emissions are distributed to the regions where these emissions are emitted (Cai et al., 2017; Fernández-Amador et al., 2017; Peters, 2008). This accounting is more widely adopted by policy makers. For example, the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol have both adopted production-based accounting (Dong, 2017). By comparison, under consumption-based accounting, also known as the carbon footprint approach, all emissions that occur along the chains of production are allocated to the final consumers of the products (Ang and Choi, 1997; Wiedenhofer et al., 2017). Therefore, emissions embodied in one region's imports belong to the consumption-based emissions of the region. Consumption-based emissions are usually calculated using environmentally extended input-output analysis (EEIOA) (Peters et al., 2011; Yu et al., 2017). Most studies of consumption-based emissions are conducted at the global or national levels. Recently, some studies used EEIOA to analyse carbon emissions for Chinese cities from a consumption perspective. For example, Mi et al. (2016) used an input-output model to estimate consumption-based carbon emissions for 13 cities in China. They found that large differences existed between consumption- and production-based accounting for all cities examined. Feng et al. (2014) calculated consumption-based emissions of four cities in China and estimated the spatial distribution of the emissions within China that were caused by consumption in the four cities.

In this study, we construct production-based carbon emission inventories for Shanghai from 2000 to 2015 and estimate consumption-based carbon emissions for 2007, 2010, and 2012. We use a global MRIO model that combines China's MRIO with a global MRIO model that is based on the Global Trade and Analysis Project (GTAP). Based on the global MRIO model, we use the EEIOA approach to estimate consumption-based emissions in Shanghai and emission flows between Shanghai and other regions.

2. Literature review

The relationships between economic structure and carbon emissions have been analysed via three approaches, including econometrics, decomposition analysis, and optimization model. First of all, many researchers applied econometric approaches to estimate the relationships between economic structure and carbon emissions. Ahmad et al. (2016) combined autoregressive distributed lag (ARDL) and vector error correction model (VECM) to analyse the relationships among carbon emissions, energy consumption and economic growth in India. Kofi Adom et al. (2012) used ARDL approach to estimate the short-run causal relationships and the long-run equilibrium relationships between industrial structure and carbon emissions for three African countries. Niu et al. (2011) used panel data based econometric approaches to evaluate the causality between energy consumption, GDP growth and carbon emissions for eight Asia-Pacific countries from 1971 to 2005.

Second, the decomposition analysis is widely used to analyse the relationship between economic structure and carbon emissions. Mi et al. (2017a) used structural decomposition analysis (SDA) method to analyse the impacts of China's economic structure changes on carbon emissions during 2005-2012. Mi et al. (2017b) used SDA approach based on MRIO table to estimate the impacts of economic structure changes on interregional carbon emission flows within China between 2007 and 2012. Chang and Lahr (2016) combined SDA and linkage analysis to identify the key factors and sectors that affected carbon emissions in China. Hoekstra et al. (2016) used SDA to estimate the contributions of international sourcing to global CO_2 emission growth.

Third, some researchers developed optimization models to estimate impacts of economic structure on carbon emissions. Mi et al. (2015) developed an optimization model based on input-output analysis to analyse the impacts of industrial structure changes on energy consumption and carbon emissions in China. Yu et al. (2016) developed a dynamic multi-objective optimisation model to estimate the impacts of industrial structure on energy consumption in China.

3. Methodology and data

3.1 Construction of the production-based carbon emission inventory

Production-based carbon emissions are calculated using the Intergovernmental Panel on Climate Change (IPCC) reference approach (Liu et al., 2015; Shan et al., 2017). In this study, we focus on CO_2 emissions caused by energy consumption in economic sectors. We do not consider emissions caused by industrial processes, such as the production of cement and lime. According to the IPCC approach, the formula for calculating CO_2 emissions from energy consumption is (Mi et al., 2017b)

$$C = E \times V \times F \times O, \tag{1}$$

where C represents the fossil fuel-related CO_2 emissions, E represents the energy consumption associated with different fuel types (expressed as a physical unit), V is the net calorific value of different fuel types, F is the carbon content that reflects CO_2 emissions when unit heat is released, and O is the oxygenation efficiency of different fuel types. The fossil fuel consumption for all provinces in China is calculated as follows:

$$\begin{aligned} E = {} & \text{Total final consumption} + \text{Input for thermal power} + \text{Input for heating} \\ & - \text{Used as chemical material} - \text{Loss} \end{aligned}. \tag{2}$$

Based on the IPCC approach, we construct production-based CO_2 emission inventories for 30 sectors in 30 Chinese regions from 2000 to 2015. For each sector, carbon is emitted from 17 types of energy, including 8 coal products, 8 oil products, and natural gas.

3.2 Environmentally extended input-output analysis

The EEIOA is an approach to estimate the linkages between economic activities and environmental impacts (Su and Ang, 2012). The approach has been widely used in environmental economic fields, such as air pollution (Lin et al., 2016; Yang et al., 2016), water use (Cazcarro et al., 2013; Ewing et al., 2012), land use (Costello et al., 2011; Weinzettel et al., 2013), biodiversity loss (Lenzen et al., 2012; Lenzen and Murray,

2001) and material use (Weisz and Duchin, 2006; Wiedmann et al., 2015). We perform EEIOA on carbon emissions based on an MRIO model. The MRIO model describes economic connections among 26 provinces and 4 cities in China. Using the MRIO model, we can estimate CO_2 emissions embodied in interregional trade and the contributions of different final demand categories (i.e., household and government consumption, investment, exports and imports) relative to the emissions for each region. In this study, we focus on production- and consumption-based CO_2 emissions of Shanghai city. The foundations of the MRIO model are the linear relationships between total output, production structure and final use, as follows:

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{F}, \tag{3}$$

$$\mathbf{X} = \begin{bmatrix} \mathbf{X}^1 \\ \mathbf{X}^2 \\ \vdots \\ \mathbf{X}^n \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \cdots & \mathbf{A}^{1n} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \cdots & \mathbf{A}^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{n1} & \mathbf{A}^{n2} & \cdots & \mathbf{A}^{nn} \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} \mathbf{f}^{11} & \mathbf{f}^{12} & \cdots & \mathbf{f}^{1n} \\ \mathbf{f}^{21} & \mathbf{f}^{22} & \cdots & \mathbf{f}^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{f}^{n1} & \mathbf{f}^{n2} & \cdots & \mathbf{f}^{nn} \end{bmatrix}, \tag{4}$$

where $\mathbf{X} = \left(X_i^s\right)$ is the vector of the total output and X_i^s is the total output of sector i in region s. I is the identity matrix, and $\left(\mathbf{I} - \mathbf{A}\right)^{-1}$ is the Leontief inverse matrix. The technical coefficient submatrix $\mathbf{A}^{rs} = \left(a_{ij}^{rs}\right)$ is given by $a_{ij}^{rs} = z_{ij}^{rs} / x_j^s$, in which z_{ij}^{rs} represents the intersectoral monetary flows from sector i in region r to sector j in region s, and x_j^s is the total output of sector j in region s. $\mathbf{F} = \left(f_i^{rs}\right)$ is the final demand matrix, and f_i^{rs} is the final demand of region s for the goods of sector i from region r.

The main functions of EEIOA are to calculate CO_2 emissions embodied in goods and services and to transfer production-based emissions into consumption-based emissions (Liu et al., 2017; Liu et al., 2016). Consumption-based carbon emissions can be calculated by

$$C = \mathbf{K}\left(\mathbf{I} - \mathbf{A}\right)^{-1}\mathbf{F}, \tag{5}$$

where C represents the total emissions embodied in goods and services used for final demand, and $\mathbf{K}$ is a vector of the carbon intensity for all economic sectors in all regions.

3.3 Linking China's MRIO to the GTAP database

The imports of Shanghai city are divided into domestic imports (from China's other regions) and international imports (from foreign countries). The emissions embodied in domestic imports can be estimated by performing EEIOA based on the Chinese MRIO model. With respect to the emissions embodied in international imports, some previous studies assumed that the emission intensity of imports is the same as that of domestic products (Guan et al., 2008). This approach may cause large errors in emission estimation because the carbon intensity of imports is considerably different from that of domestic products due to different technology levels. Therefore, China's exports and imports are linked to a global MRIO table that is based on the GTAP database (Aguiar et al., 2016). The GTAP database describes international trade connections for 57 economic sectors among 140 regions. The imports (or exports) in each sector in each Chinese region are distributed among all other 139 regions of the world based on the GTAP model. We aggregate the 57 sectors of GTAP model into 30 sectors to link China's imports and exports with other countries. Please see Table A1 for the concordance of sectors for Chinese MRIO and GTAP database. Therefore, we obtain a new Chinese GTAP MRIO model that includes 30 Chinese provinces and 139 countries with 30 sectors for Chinese provinces and 57 sectors for foreign countries. The emissions embodied in Shanghai's international imports are calculated based on the Chinese GTAP model.

3.4 Data sources

In this study, we mainly need two series of data: MRIO tables and energy consumption. The 2007 and 2010 Chinese MRIO tables were compiled by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (Liu et al., 2012; Liu et al., 2014). The 2012 Chinese MRIO tables were compiled in our previous study (Mi et al., 2017b). These Chinese MRIO tables were all compiled using a modified gravity model. The global MRIO tables were obtained from version 9 of the GTAP database, which describes the economic linkages for 57 sectors across 140 regions (Aguiar et al., 2016). The energy consumption data for all provinces were obtained from the China Energy Statistical Yearbooks (National Bureau of Statistics, 2015). The emission factors are critical for calculating carbon emissions using the IPCC approach. The most widely used emission factors are the IPCC default values. However, recent studies have indicated that the IPCC default values overestimate China's carbon emissions. Table 1 shows the emission factors used in this study (Liu et al., 2015; Mi et al., 2017a).

Table 1 Emission factors for different energy types used to calculate CO_2 emissions.

No.	Energy types	Net calorific value (PJ / $10^4\ t, 10^8\ m^3$)	Carbon content (Mt CO_2 / PJ)	Oxygenation efficiency (%)
1	Raw coal	0.20908	0.087464	88.535
2	Cleaned coal	0.26344	0.087464	88.535
3	Other washed coal	0.15393	0.087464	88.535
4	Briquettes	0.17796	0.087464	88.535
5	Coke	0.28435	0.104292	97.000
6	Coke oven gas	1.63080	0.071414	99.000
7	Other gas	0.84290	0.071414	99.000
8	Other coking products	0.28435	0.091212	97.000
9	Crude oil	0.41816	0.073284	98.000
10	Gasoline	0.43124	0.069253	98.000
11	Kerosene	0.43124	0.071818	98.000
12	Diesel oil	0.42652	0.074017	98.000
13	Fuel oil	0.41816	0.077314	98.000
14	Liquefied petroleum gas (LPG)	0.50179	0.063024	99.000
15	Refinery gas	0.46055	0.073284	99.000
16	Other petroleum products	0.41816	0.074017	98.000
17	Natural gas	3.89310	0.056062	99.000

Note: The units of net calorific value for coke oven gas, other gas, and natural gas are PJ / $10^8\ m^3$, while units are PJ / $10^4\ t$ for other energy types.

4. Results and discussion

4.1 Carbon emissions from production perspectives

The proportions of Shanghai's production-based carbon emissions, relative to China's total emissions, declined from 4.1% in 2000 to 2.1% in 2015. The production-based carbon emissions in Shanghai increased by 56% from 2000 to 2015 (Table 2), while the GDP increased by 324% during the same period. As a result, the direct carbon intensity in Shanghai has been declining since 2000. The changes in carbon emissions in Shanghai city can be divided into three phases. First, carbon emissions increased rapidly before the global financial crisis. The average annual growth rate of carbon emissions was 5.2% during the 2000-2008 period and was mainly due to the rapid economic development and corresponding increase in energy use. Second, the carbon emission growth rate declined after the global financial crisis. Carbon emissions increased by 3.8% per year during the 2008-2011 period, peaking at 188 million tonnes (Mt) in 2011. This was mainly caused by the 2008 global financial crisis, which greatly affected China's as well as Shanghai's economy. Although the Chinese central government and the Shanghai local government implemented many measures to mitigate the impacts of the crisis, such as the Four Trillion Yuan (US$600 billion) Stimulus Package, Shanghai's economic growth declined. Third, carbon emissions have exhibited downward trends in recent years. Carbon emissions declined by 7% between 2011 and 2015. Shanghai's economy has been unable to continue the double-digit growth of previous decades. Instead, it has entered a "new normal" socioeconomic development phase, which aims to achieve better quality (more sustainable and inclusive) economic growth. As a result, energy consumption and corresponding carbon emissions in Shanghai have declined. In summary, production-based carbon emissions in Shanghai increased rapidly before the global financial crisis but have declined in the new normal.

From the perspective of energy types, the decline of Shanghai's production-based emissions was due to the decrease in coal-related emissions. Coal consumption was responsible for more than half of Shanghai's production-based emissions. However, the proportions of coal-related emissions relative to Shanghai's total emissions declined from 73% in 2000 to 54% in 2015 (Table 2). By comparison, the proportions of carbon emissions related to oil and natural gas increased from 27% and 0.3% to 39% and 7%, respectively, during the same period. Carbon emissions caused by oil and natural gas continued to increase from 2000 to 2015. In recent years, however, emissions caused by coal declined by 18% from 2011 to 2015, which resulted from the 20% decline in coal consumption in Shanghai.

Table 2 Production-based carbon emissions from different energy types in Shanghai.

Year	Coal		Oil		Natural gas		Total (Mt)
	Emission (Mt)	Proportion	Emission (Mt)	Proportion	Emission (Mt)	Proportion	
2000	82.24	73.16%	29.86	26.56%	0.31	0.28%	112.41
2001	84.95	72.47%	32.01	27.31%	0.26	0.22%	117.22
2002	85.99	69.93%	35.16	28.60%	1.80	1.47%	122.95
2003	88.86	68.08%	41.17	31.54%	0.50	0.38%	130.53
2004	93.17	65.81%	47.31	33.42%	1.09	0.77%	141.57
2005	96.45	64.07%	51.76	34.38%	2.34	1.55%	150.55
2006	94.96	61.05%	57.10	36.71%	3.48	2.24%	155.54
2007	99.32	60.25%	61.33	37.20%	4.21	2.55%	164.85
2008	102.44	60.78%	61.89	36.72%	4.22	2.50%	168.55
2009	100.34	59.51%	63.88	37.88%	4.41	2.61%	168.63
2010	104.29	59.07%	65.50	37.09%	6.78	3.84%	176.56
2011	115.25	61.15%	64.40	34.17%	8.81	4.67%	188.46
2012	106.16	58.29%	65.49	35.96%	10.49	5.76%	182.13
2013	111.25	59.26%	65.65	34.97%	10.85	5.78%	187.75
2014	98.43	56.53%	64.81	37.22%	10.87	6.24%	174.12
2015	94.60	54.08%	67.40	38.53%	12.92	7.39%	174.92

From a sectoral perspective, the decline of Shanghai's production-based emissions was due to the decrease in emissions from energy sectors (i.e., electricity, hot water, and gas production and supply). Between 2011 and 2015, CO_2 emissions caused by energy sectors declined by 21%, i.e., from 75 million tonnes (Mt) to 60 Mt. Shanghai has been transferring its high carbon-intensive energy sectors to China's other regions. By contrast, electricity imported from other provinces to Shanghai increased by 74%, from 37 billion kW·h in 2011 to 65 billion kW·h in 2015. Notably, the energy sector was the largest contributor of Shanghai's production-based emissions in 2015, accounting for 34% of total emissions. Transport, as well as metal and nonmetal products, also emitted large amounts, contributing 24% and 22%, respectively, of Shanghai's total emissions in 2015 (Figure 1). Due to changes in the production structure, the proportions of carbon emissions related to the service industry increased considerably from 14% in 2000 to 32% in 2015. Most of the emissions from the service industry were caused by the transport sector, which accounted for 24% of Shanghai's total emissions in 2015.

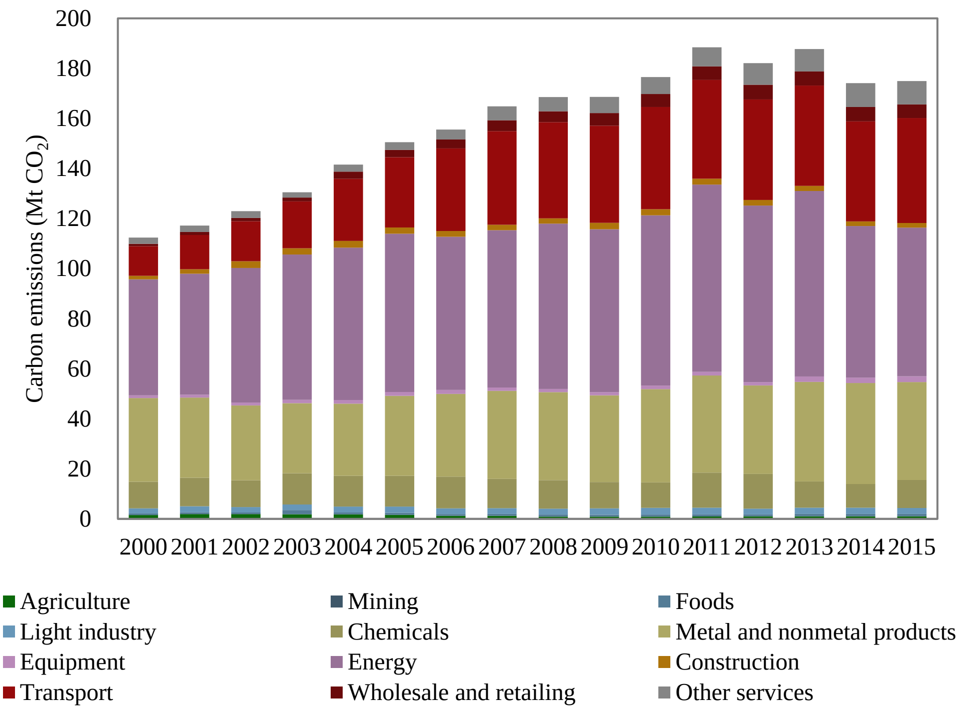

Figure 1. Production-based carbon emissions from different sectors in Shanghai. Please see Table A2 in Appendix for the breakdown by sector.

Carbon emissions caused by direct energy use of households cannot be analysed in input-output models. With the improvements of living standards, emissions caused by direct energy use of households in Shanghai increased greatly by 166% between 2000 and 2015 (Figure 2). From energy type perspective, the proportions of emissions caused by direct coal use declined from 65% in 2000 to 4% in 2015, while the proportions of those caused by oil and natural gas use increased from 31% and 3% to 73% and 24%, respectively. Generally speaking, direct energy use in Shanghai's households have been cleaner. In addition, direct carbon emissions from rural households have declined since 2013, while those from urban households have been increasing since 2000. The urbanization is one of the reasons for the reduction of rural direct carbon emissions. In 2012, direct carbon emissions from urban households are 3.7 times of those from rural households.

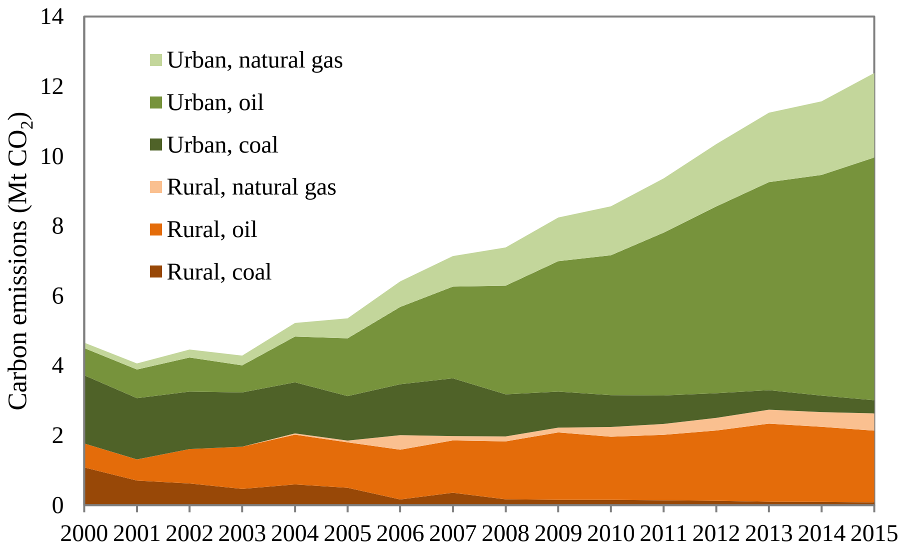

Figure 2. Carbon emissions caused by direct energy use of households in Shanghai city.

4.2 Carbon emissions from consumption perspectives

We estimated consumption-based carbon emissions of Shanghai for 2007, 2010, and 2012, because the MRIO tables are only available for these three years. Shanghai is a typical consumption city, and its consumption-based carbon emissions are much higher than its production-based emissions. In 2012, consumption-based carbon emissions in Shanghai reached 240 Mt, which was 32% higher than its production-based emissions (i.e., 182 Mt). China is a vast country with considerable regional variations in economic development and lifestyles. Equal distribution of responsibilities to reduce carbon emissions is critical to mitigate climate change in China. The country has considered equality in its climate change actions. For example, the government aims to reduce its energy intensity and carbon intensity by 15% and 18%, respectively, during the 13th five-year period (2016-2020). Most of the rich eastern provinces (such as Beijing and Shanghai) are required to reduce energy intensity by 17%, while the targets for some poor western provinces (such as Qinghai and Xinjiang) are 10%. However, these policies are mostly based on production-based accounting. The selection of an emission accounting system has strong impacts on the distribution of climate change-related responsibilities. The two accounting approaches (i.e., production- and consumption-based accounting) need to be used comprehensively to identify equitable climate policies.

The proportions of Shanghai's consumption-based carbon emissions relative to China's total emissions declined from 4.9% in 2007 to 3.2% in 2012. Shanghai's consumption-based carbon emissions increased by 15.2% during the 2007-2010 period and decreased by 3.4% during the 2010-2012 period (Figure 3). We explored the reasons for this emission reduction from three perspectives: final use categories, consumption patterns, and spatial origins.

From the perspective of final use categories, the decline of Shanghai's consumption-based carbon emissions was mainly due to the decrease in emissions related to household consumption and capital formation (Figure 3a). Capital formation contributes the largest part of Shanghai's consumption-based emissions, but its proportion relative to total emissions has declined. Capital formation generated 119 Mt, 115 Mt, and 111 Mt in 2007, 2010, and 2012, which accounted for 55.0%, 46.3% and 46.2%, respectively, of Shanghai's consumption-based emissions. Emissions related to household consumption increased from 85 Mt in 2007 to 113 Mt in 2010, followed by a decline to 106 Mt in 2012.

From the perspective of consumption patterns, the decline of Shanghai's consumption-based carbon emissions was mainly due to the decrease in emissions embodied in secondary industry products (Figure 3b). There are substantial differences in the embodied carbon intensity of different products, with much higher intensities for secondary industry products. For example, the embodied carbon intensity of the energy sector is five times that of the transport sector. For Shanghai, emissions embodied in secondary industry products contributed more than 80% of total consumption-based emissions, but this declined by 7% from 2010 to 2012. By comparison, emissions embodied in primary and tertiary industry products continued to increase from 2007 to 2012. As a result, proportions of emissions embodied in tertiary industry products increased from 10% to 15%.

From the perspective of spatial origins, the decline of Shanghai's consumption-based carbon emissions was mainly due to the decrease in domestic imported emissions (Figure 3c). Consumption-based emissions in Shanghai include territorial emissions (embodied in products originally produced in Shanghai), domestic imported emissions (embodied in products originally produced in China's other regions), and international imported emissions (embodied in products originally produced abroad). More than 70% of Shanghai's consumption-based emissions are imported from other regions, which demonstrates that consumers in Shanghai rely greatly on goods and services produced elsewhere in China. With respect to Shanghai's consumption-based emissions, territorial emissions increased by 55% between 2007 and 2012. However, domestic imported emissions declined by 26% between 2010 and 2012. As a result, the proportion of domestic imported emissions relative to Shanghai's total emissions decreased from 65% in 2010 to 50% in 2012.

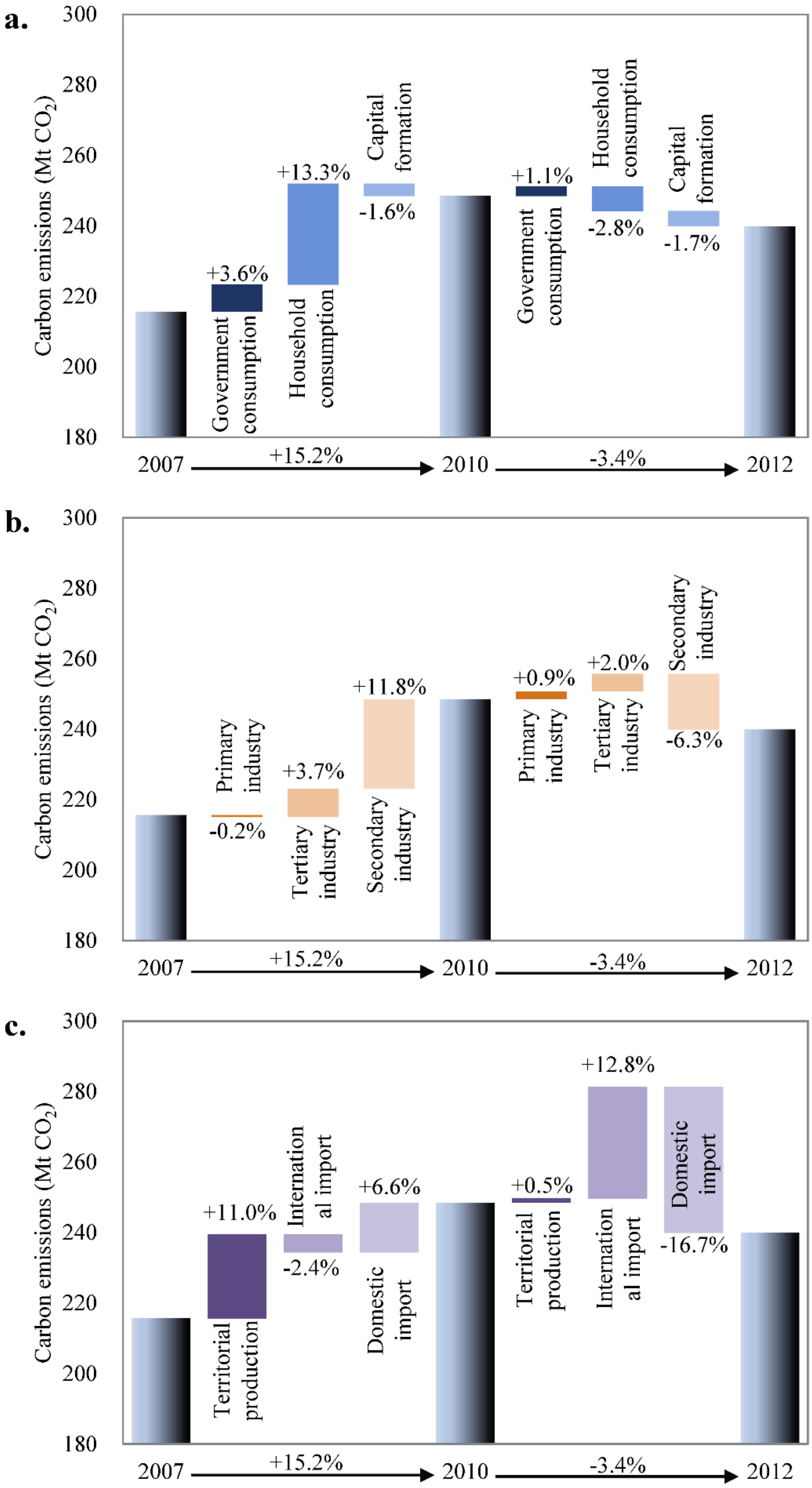

Figure 3. Consumption-based carbon emissions in Shanghai city in 2007, 2010, and 2012. Figure 3a, 3b, and 3c demonstrate the emission changes from the perspectives of final use categories, consumption patterns, and spatial origins, respectively.

4.3 Interregional carbon emission flows

We estimated the carbon emissions embodied in trade among 30 Chinese regions based on the MRIO model and focused on carbon emission flows related to Shanghai. As one of the richest cities in China, Shanghai imports large amounts of CO_2 emissions from other regions. The city imports many low-value-added and high-carbon-intensive products from less developed provinces in China and exports high-value-added and low-carbon-intensive products. In other words, consumers in Shanghai are being supported by CO_2 emitted in the other poorer regions of China.

In 2007, all net emission flows from other regions to Shanghai were positive (Figure 4a). Emissions embodied in products originally produced in other regions and finally consumed in Shanghai were 148 Mt CO_2, which accounted for 69% of Shanghai's total consumption-based emissions. In addition, Shanghai also exported 42 Mt CO_2 to other regions. Therefore, the total net emission flows from other regions to Shanghai were 106 Mt. Among China's eight regions, Central and North China exported the highest amount of carbon emissions to Shanghai, i.e., net emission flows of 31 Mt and 28 Mt, respectively.

In 2010, the net emission flows from Beijing-Tianjin to Shanghai were negative (Figure 4b). In other words, Shanghai imported 4.5 Mt CO_2 from Beijing-Tianjin, which was lower than the emissions embodied in Shanghai's exports to Beijing-Tianjin (7.6 Mt). Central and North China were the regions responsible for the largest net emission flows to Shanghai (39 Mt and 26 Mt, respectively).

The net emission flows from China's other regions to Shanghai declined considerably (Figure 4b). The emission inflows into Shanghai declined by 26% (or 42 Mt) from 2010 to 2012, while the emission outflows from Shanghai increased by 40% (or 23 Mt). As a result, the net emission flows from China's other regions to Shanghai decreased by 60%, from 105 Mt in 2010 to 41 Mt in 2012. The decline in net emission flows is mainly because of the changes in Shanghai's import and export structure. In 2010, Shanghai's import value from other provinces was 32% higher than its export value. In 2012, however, Shanghai's import value from other provinces was 16% lower than its export value. From a spatial perspective, net emission flows from Central and North China declined by 26% and 20%, respectively. From a sectoral perspective, net emission inflows attributed to the energy sector declined by 40 Mt, which accounted for 62% of the total decline in Shanghai's net emission inflows.

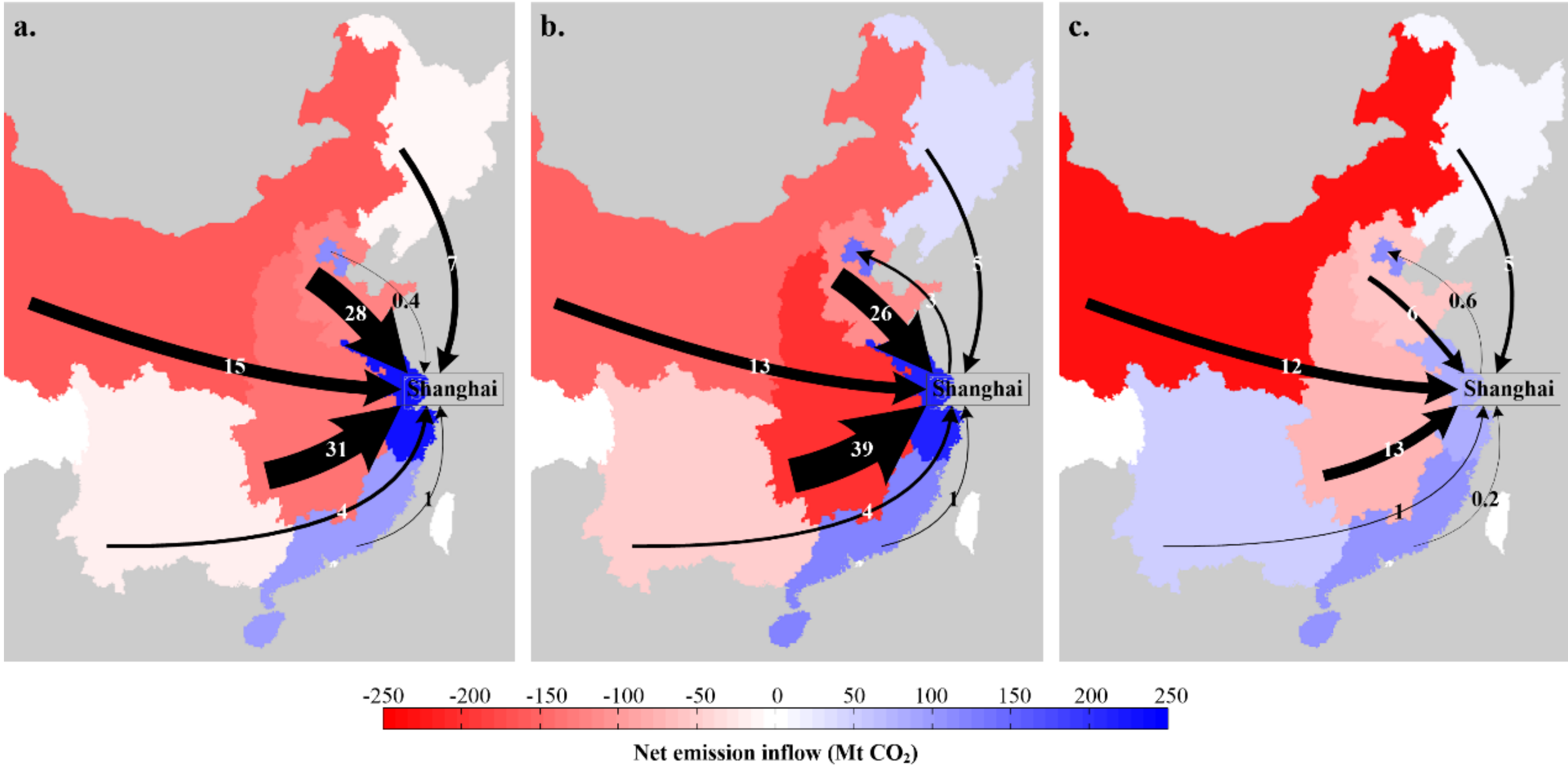

Figure 4. Domestic net emission flows between Shanghai and China's other regions. Figure 4a, 4b, and 4c demonstrate emission inflows in 2007, 2010, and 2012, respectively. The sizes of the arrows correspond to the magnitude of the net emission flows between Shanghai and other regions.

5. Conclusions

Changes in the economic structure have great impacts on CO_2 emissions in Shanghai in terms of both production and consumption perspectives. Shanghai's production-based emissions declined between 2011 and 2015 due to changes in the production structure and energy mix. In the new normal, China aims to transform its economic development mode and achieve better quality economic growth that is more inclusive and sustainable. The country is struggling to eliminate dependence on coal-based heavy industry during its economic development. In Shanghai, CO_2 emissions attributed to the energy sector declined by 21% between 2011 and 2015, while the proportions of carbon emissions in the service industry increased greatly. In terms of the energy mix, the proportion of coal consumption declined considerably in recent years. The emissions caused by coal consumption declined by 18% from 2011 to 2015, while emissions caused by oil and natural gas consumption increased.

Shanghai's consumption-based CO_2 emissions declined between 2007 and 2012, mainly due to changes in consumption patterns and domestic interregional emission flows. Lifestyle has a strong impact on consumption-based CO_2 emissions, as there are substantial differences in embodied carbon intensity for different products. In recent years, the consumption patterns in Shanghai have become less carbon intensive; emissions embodied in secondary industry products declined by 7% from 2010 to 2012. From the perspective of spatial origin, Shanghai's economy is significantly supported by China's other regions. In China, large amounts of CO_2 emissions are transferred from poorer western and central China to richer eastern coastal China (including Shanghai). In recent years, however, these emission flows have declined greatly. Domestic imported emissions in Shanghai decreased by 26% between 2010 and 2012. This was mainly due to the more rapid growth in the economy and consumption in western than in eastern China, although eastern China remains considerably more affluent.

We argue that the carbon emission flows from western China to Shanghai may further decline in the near future. China is struggling to narrow the gap between the east and west. China implemented the Western Development Strategy at the turn of the century and has set preferential policies to spur economic growth in the west. The strategy has entered its second phase (i.e., 2010-2030), during which western regions are expected to achieve faster economic and consumption growth. Therefore, the demands of final use products may continue to increase more rapidly in western than in eastern China. In addition, China has proposed the Belt and Road (B&R) initiative, under which trade between the western Chinese regions and the rest of Eurasia will be promoted. Therefore, western China will need more support from eastern China to produce products that are exported to foreign countries.

Although this paper demonstrates the impacts of economic structure changes on city-level carbon emissions in China, there are still several limitations. First, we only consider consumption-based carbon emissions in Shanghai in 2007, 2010, and 2012, due to data unavailability. Recent economic structure changes in China might have great impacts on consumption-based CO_2 emissions in Shanghai. Therefore, it will be meaningful to estimate consumption-based emissions in recent years when data (e.g., input-output tables) are available. Second, the carbon emissions caused by industrial processes (e.g., production of cement and lime) are not considered in this study. We mainly focus on relationships among economic development, energy consumption and carbon emissions. Industrial processes also cause plenty of greenhouse gas emissions and can be considered in the future studies.

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Appendix A

Table A1 Concordance of sectors for Chinese MRIO and GTAP database.

No.	Sectors for Chinese MRIO	Sectors for GTAP database
1	Agriculture	Paddy rice
		Wheat
		Cereal grains nec
		Vegetables; fruit; nuts
		Oil seeds
		Sugar cane; sugar beet
		Plant-based fibers
		Crops nec
		Bovine cattle; sheep and goats; horses
		Animal products nec
		Raw milk
		Wool; silk-worm cocoons

		Forestry
		Fishing
2	Coal mining	Coal
3	Petroleum and gas	Oil
		Gas
4	Metal mining	Minerals nec
5	Nonmetal mining	
6	Food processing and tobaccos	Bovine meat products
		Meat products nec
		Vegetable oils and fats
		Dairy products
		Processed rice
		Sugar
		Food products nec
		Beverages and tobacco products
7	Textile	Textiles
8	Clothing, leather, fur, etc.	Wearing apparel
		Leather products
9	Wood processing and furnishing	Wood products
10	Paper making, printing, stationery, etc.	Paper products; publishing
11	Petroleum refining, coking, etc.	Petroleum; coal products
12	Chemical industry	Chemical; rubber; plastic products
13	Nonmetal products	Non-metallic minerals
14	Metallurgy	Ferrous metals
15	Metal products	Metals nec
		Metal products
17	Transport equipment	Motor vehicles and parts
		Transport equipment nec
19	Electronic equipment	Electronic equipment
16	General and specialist machinery	Machinery and equipment nec
18	Electrical equipment	
20	Instrument and meter	
21	Other manufacturing	Manufactures nec
22	Electricity and hot water production and supply	Electricity
23	Gas and water production and supply	Gas manufacture; distribution
		Water
24	Construction	Construction
26	Wholesale and retailing	Trade
27	Hotel and restaurant	
25	Transport and storage	Transport nec

		Water transport
		Air transport
28	Leasing and commercial services	Communication
		Financial services nec
		Insurance
		Business services nec
		Dwellings
29	Scientific research	Recreational and other services
30	Other services	Other services

Table A2 Aggregation of sectors.

Codes	Aggregated sectors	Sectors for Chinese MRIO
S1	Agriculture	Agriculture
S2	Mining	Coal mining
		Petroleum and gas
		Metal mining
		Nonmetal mining
S3	Food	Food processing and tobacco
S4	Light industry	Textile
		Clothing, leather, fur, etc.
		Wood processing and furnishing
		Paper making, printing, stationery, etc.
S5	Chemicals	Petroleum refining, coking, etc.
		Chemical industry
S6	Metal and nonmetal products	Nonmetal products
		Metallurgy
		Metal products
		General and specialist machinery
S7	Equipment	Transport equipment
		Electrical equipment
		Electronic equipment
		Instruments and meters
		Other manufacturing
S8	Energy	Electricity and hot water production and supply
		Gas and water production and supply
S9	Construction	Construction
S10	Transport	Transport and storage
S11	Wholesale and retail	Wholesale and retail
S12	Other services	Hotels and restaurants
		Leasing and commercial services

	Scientific research
	Other services

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