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Provincial emission accounting for CO_2 mitigation in China: Insights from production, consumption and income perspectives

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HIGHLIGHTS

- Provincial CO_2 emissions of China are investigated from different perspectives.
- Embodied emission flows driven by final demands and primary inputs are quantified.
- Income-based emissions are relatively higher in energy resource-abundant province.
- Tertiary industries are the major contributors to China's income-based emissions.

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ABSTRACT

Emission accounting can help to identify main CO_2 emitters and inform emission mitigation policymaking. Previous studies have proved that the application of different accounting principles results in different emission levels, thus bring different policy implications, while the emissions enabled by primary inputs (or income-based emission) have been overlooked in studies for carbon mitigation in China. Understanding the role of primary inputs in CO_2 emissions is a prerequisite to create efficient supply-side mitigation policies. Here, we conduct a quantitative study of China's provincial production-, consumption-, and income-based CO_2 emissions in a unified multi-regional input-output analysis framework. The results are compared from the three perspectives for 30 provinces in China to help the government identify the main policy targets from production, demand, and supply sides. We found that 64% and 35% of China's emissions are transferred among provinces driven by final demands and primary inputs, respectively. Mitigation policies in heavily industrialized provinces, such as Hebei, Liaoning, and Henan, where the production-based emissions are higher than the consumption- and income-based emissions, should be focused on production side. Similarly, policies in eastern coastal developed provinces and resource-abundant provinces should be focused on demand- and supply-side, respectively. Moreover, we found that tertiary industries, which previous studies generally regard as low-carbon industries, are the major contributors to China's income-based CO_2 emissions with a total of 2026 Mt or 31% of China's total income-based CO_2 emissions. Thus, expanding tertiary industries without reducing their industrial linkages to carbon-intensive industries is not conducive to China's emission reduction.

1. Introduction

In response to global climate change and domestic environmental concerns, China committed to reach its carbon emissions peak around 2030, and to cut its carbon emissions per unit of GDP by 60–65% from 2005 levels. After the conference at the 2015 United Nations Climate Change Conference, the Chinese government strengthened the domestic policy targets for an earlier peak and made great efforts toward deep decarbonization [1,2]. Some of the latest official policy documents provide very detailed objectives and guidance for carbon mitigation in China [3], such as the *National Strategy on Energy Production and Consumption Revolution (2016–2030)* and the *13th Five Year Plan for Energy Conservation and Emission Reduction Programme*.

However, most of China's current mitigation policies target reducing emissions on the production side by changing the energy mix and optimizing the sectoral structure [4], as the domestic economy is

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heavily reliant on fossil-energy (e.g., coal and crude) and carbon-intensive sectors (e.g., Coking and Electricity supply) [5,6]. The roles of final demand and primary input (value added) in driving emissions have long been ignored.

In addition, China has more than 30 provinces with huge regional disparity in economic development and CO_2 emissions [7,8]. A precise and efficient province- and responsibility-specific emission reduction management plan is urgently needed for policy makers [9]. In other words, China's government needs to introduce differentiated CO_2 mitigation policies to various provinces and facilitate interprovincial emission reduction cooperation to meet its overall reduction targets. The first step is to quantify the provincial CO_2 emissions of various sectors, which is essential for understanding the roles of the provinces in China's CO_2 emissions [10].

The CO_2 emissions that are directly generated by the production processes of local sectors, which is typically called "production-based CO_2 emissions", can be calculated with energy use and their CO_2 emission coefficients [11]. However, as interprovincial trade is increasing in China, more and more emissions are embodied in goods and services which are traded between provinces [12,13]. The production-based accounting method cannot capture the emissions embodied in inter-regional trade [14,15]. Thus, if the government only looks at the production-based CO_2 emissions, excessive emission reduction targets and overly strict policies will be allocated to provinces whose high local direct emissions are produced to meet the final demands of other provinces.

To address this matter, some studies have suggested accounting for the upstream CO_2 emissions generated to produce a region's final demand, which is generally referred to as "consumption-based CO_2 emissions" [16,17]. The consumption-based accounting method can quantify both the direct and supply chain effects of final demand and household lifestyle on CO_2 emissions, and then provide guidance for demand-side emission reduction policies [18,19]. The method that has been widely used in consumption-based accounting is the environmental extended multi-regional input-output model (MRIO), in which the environmental-related data is combined with an input-output table to track the embodied environmental flows among industrial sectors and regions [20,21]. Studies of consumption-based accounting for environmental elements such as carbon emission [22,23], water [24–26], energy [27,28] and land [29,30] have revealed different regional environmental implications over the production-based accounting methods [31].

Although consumption-based accounting can address the limitations of the production-based accounting approach and can supplement the production-based accounting method by tracing upstream emissions at the end of the supply chain (final demand) [32–34], they both neglect the effects of primary inputs (e.g., labor forces, capital, and government services) on carbon emissions and are weak in guiding supply-side policy [35–37]. The primary inputs (value added) are created from the production activities at the beginning of the supply chain and then trigger downstream emissions in local and other regions [38]. As the payments to primary factors of production, regions receive income such as wages, capital profits and tax. Therefore, the emissions enabled by primary inputs are often referred to as "income-based CO_2 emissions" [39], which include all the emissions generated downstream in the supply chain until delivery to final demand and can help to identify critical primary suppliers for supply-side emission reduction policy-making [40]. In addition, income-based emissions might also correspond with the ability to pay, given the large economic gain of the region from their production activities. This should not be ignored when allocating carbon mitigation responsibility and targets.

The importance of income-based emission in guiding the division of emission reduction responsibilities among nations has been emphasized by Steininger et al. [40] Marques et al. [41] and Liang et al. [39]. Their studies highlighted the role of fossil fuel exporters in driving global CO_2 emissions at supply side, and suggested that countries such as Russia and Australia should take more responsibility for cutting emissions, even though those countries have relatively lower production- and consumption-based emissions compared to other countries. Liu and Fan [42] studied emissions enabled by primary inputs in a global multi-regional input-output (MRIO) model and observed that developing nations have lower income-based emissions compared to their production-based emissions. This means that their benefits from emissions do not match the environmental costs. However, studies cited above mainly focused on emission reduction responsibilities, not on policy implication for emission reduction in some major carbon emitters (e.g. China, US, and India). Several empirical studies have discussed the income-based emissions in China, and compared them to emissions based on other accounting principles. Zhang [43] calculated China's carbon emissions from various perspectives, include income-based perspective. However, his study showed neither provincial emission mitigation policy implications based on the difference of emissions under different accounting principles nor full pictures of emissions flow driven by final demand and enabled by primary inputs. Li et al. [44] and Feng et al. [45] conducted similar studies for Beijing and China, respectively. However, their studies failed to show the income-based emissions of all provinces in China, which is essential to the formulation of differentiated CO_2 mitigation policies for various provinces.

In summary, all three accounting methods should be used in provincial emission accounting to help China's government identify the main policy targets from production, final demands, and primary inputs. Here, we use the latest 2012 China MRIO table to quantify the production-, consumption-, and income-based CO_2 emissions for provinces in China, as well as the flows of embodied emissions that are driven by final demands and enabled by primary inputs. Subsequently, we provide implications for guiding the design of effective and fair policies toward production, demand, and supply sides that are aimed at reducing overall carbon emissions in China.

Compared to previous studies, our work investigated China's provincial production-based, consumption-based and income-based CO_2 with one integrated MRIO model. This allow us to understand the role of each province's producers, final consumers and primary suppliers in driving China's CO_2 emissions. More importantly, the comparative analysis of carbon emission profile from the three perspectives for provinces can help policy makers identify the main targets of emission mitigation policies in each province. For example, supply side policies should be inducted in provinces with higher income-based emissions compared to their production- and consumption-based emissions. In addition, the description of interprovincial emission flow networks can help inform the policymaking on provincial coordinated emission reduction.

2. Methodology and data

The foundation of the MRIO model used in this study involves a MRIO table [46,47], which includes a series of rows and columns of data that quantify the inter-sector monetary flows of intermediate and final products within and among regions (see Table 1). It is a practical model for the analysis of the interactions and interdependencies between different sectors in different regions. By extending it with the direct carbon emissions data of sectors, the model is able to trace the embodied emission flows that are driven by final demands and enabled by primary inputs.

The row sum in Table 1 can be expressed as:

$$(z_{i1}^{r1}+\cdots+z_{in}^{r1}) + (z_{i1}^{r2}+\cdots+z_{in}^{r2}) + \cdots+(z_{i1}^{rm}+\cdots+z_{in}^{rm}) + f_i^{r1} + \cdots+f_i^{rm} = \sum_{s=1}^{m}\sum_{j=1}^{n} z_{ij}^{rs} + \sum_{s=1}^{m} f_i^{rs} = x_i^r \quad (1)$$

The column sum in Table 1 can be expressed as:

Table 1
The scheme of the Multi-Regional Input-Output table.

			Intermediate demand			Final demand			Total output
			Region 1 Sector 1…Sector n	… …	Region m Sector 1…Sector n	Region 1	…	Region m	
Intermediate input	Region 1	Sector1……Sector n	Z^{11}	……	Z^{1m}	F^{11}	…	F^{1m}	X^{1}
	……	……		……			……		……
	Region m	Sector1……Sector n	Z^{m1}	……	Z^{mm}	F^{m1}	…	F^{mm}	X^{m}
Primary input			$V^{1'}$	……	$V^{m'}$				
Total input			$X^{1'}$	……	$X^{m'}$				

$$(z_{1j}^{1s}+\cdots+z_{nj}^{1s}) + (z_{1j}^{2s}+\cdots+z_{nj}^{2s}) + \cdots+(z_{1j}^{ms}+\cdots+z_{nj}^{ms}) + V_j^{s'} = \sum_{r=1}^{m}\sum_{i=1}^{n} z_{ij}^{rs}+V_j^{s'} = x_i^r \quad (2)$$

The direct input coefficient, a_{ij}^{rs}, represents the direct input from sector i in region r for the production of per unit output by sector j in region s:

$$a_{ij}^{rs} = z_{ij}^{rs}/x_j^s \quad (3)$$

The direct allocation coefficient, b_{ij}^{rs}, represents the direct distribution of the per unit output of sector i in region r across sector j in region s that purchase interindustry inputs from sector i in region r:

$$b_{ij}^{rs} = z_{ij}^{rs}/x_i^r \quad (4)$$

Eq. (1) can therefore be transformed into a form containing a_{ij}^{rs}, as follows:

$$\sum_{s=1}^{m}\sum_{j=1}^{n} a_{ij}^{rs}x_j^s+\sum_{s=1}^{m} f_i^{rs} = x_i^r \quad (5)$$

Eq. (2) can therefore be transformed into a form containing a_{ij}^{rs}, as follows:

$$\sum_{r=1}^{m}\sum_{i=1}^{n} b_{ij}^{rs}x_i^r+V_j^{s'} = x_j^s \quad (6)$$

In matrix notation, Eq. (5) and Eq. (6) can be written as follows:

$$X= AX + F \quad (7)$$

$$X'= X'B + V' \quad (8)$$

or:

$$X= (I - A)^{-1}F \quad (9)$$

$$X'= V'(I - B)^{-1} \quad (10)$$

$(I - A)^{-1}$ is the Leontief Inverse, describing the total inputs of various sectors in various regions required for producing per unit final demand of a particular sector. $(I - B)^{-1}$ is the Ghosh Inverse, describing the total outputs of various sectors in various regions enabled by the per unit primary input of a particular sector.

The carbon emission intensity e_i^r, indicates the direct CO_2 emissions by sector i in region r for producing the per unit of output, and the carbon emission intensity matrix is:

$$E= [E^1, E^2,\cdots,E^m]' \quad (11)$$

We can therefore obtain the production-based CO_2 emissions, PC; consumption-based CO_2 emissions, CC; and income-based CO_2 emissions, IC; for each region by the following equations:

$$PC = E'X \quad (12)$$

$$CC = E'(I - A)^{-1}F \quad (13)$$

$$IC = V'(I - B)^{-1}E \quad (14)$$

The 2012 China MRIO table used in this study was compiled by China's Development Research Center of the State Council and the National Bureau of Statistics [48]. It is the latest MRIO table for China and includes 30 provinces, with 42 sectors in each. The data of detailed energy use by sectors in each province is collected from the statistical yearbooks of the corresponding provinces. The 42 sectors in the MRIO table are integrated into a uniform 29-sector format consistent with energy use data (see Table 2). The values of the standard coal coefficient according to various energies are collected from *China Energy Statistical Yearbook 2017* [49]. The CO_2 emissions coefficients of various energies are collected from the Intergovernmental Panel on Climate Change (IPCC) [50].

Table 2
Sector classification.

Sector code	Sector name	Sector code	Sector name
S01	Agriculture, forestry, animal and fishery	S16	General equipment
S02	Coal mining products	S17	Professional setting
S03	Oil and natural gas products	S18	Transportation equipment
S04	Metal mining products	S19	Electrical machinery and equipment
S05	Dressing and other non-metallic mineral products	S20	Communications equipment
S06	Food and tobacco	S21	Other manufactured products
S07	Textile	S22	Scrap waste
S08	Leather and feather products	S23	Electricity, heat production and supply
S09	Processed wood and furniture	S24	Gas production and supply
S10	Paper printing and educational goods	S25	Water production and supply
S11	Petroleum, coking and nuclear fuel	S26	Construction
S12	Chemical products	S27	Transportation, storage and postal services
S13	Non-metallic mineral products	S28	Accommodation and catering
S14	Metal smelting and rolling processed	S29	Other service industry
S15	Made from metal		

3. Results

3.1. Analysis of China's provincial production-based CO_2 emissions

According to the results of the production-based CO_2 emissions (Fig. 1a and b), Shandong, Hebei, Jiangsu, Henan, Inner Mongolia, Guangdong, Liaoning, and Shanxi are the main direct emitters in China, with a total of 3125 million tons CO_2 emissions, accounting for 48% of China's emissions in 2012. Most of them are located in the north of China and mainly consume fossil fuels such as coal, coke and petroleum (Fig. 1b), When we look at the sectoral contribution, most of the emissions are emitted by producers of sectors such as *Electricity and heat supply, Metal smelting and rolling processed, Chemical products, Non-metallic mineral products, Petroleum, coking, nuclear fuel*, which collectively emit 4177 million tons CO_2, accounting for 64% of the total CO_2 emissions in China. However, there are huge differences in sectoral production-based CO_2 emissions among provinces. For example, in Hebei province, production-based CO_2 emission of the *Metal smelting and rolling processed industry* reach 201 million tons, accounting for 47% of Hebei's total production-based CO_2 emissions, while the corresponding ratio in Shandong province is only 20%. The above results can help to identify key regions and sectors for production-side emission reduction policies (e.g., limiting the development of high-emission sectors, improving energy usage efficiency, and expanding the share of clean energy).

3.2. Analysis of China's provincial consumption-based CO_2 emissions

The results of China's provincial consumption-based CO_2 emissions are shown in Fig. 1c and d. By comparing the production- and consumption-based emissions, we can conclude that the final consumers in most of the developed provinces have a greater effect on China's CO_2

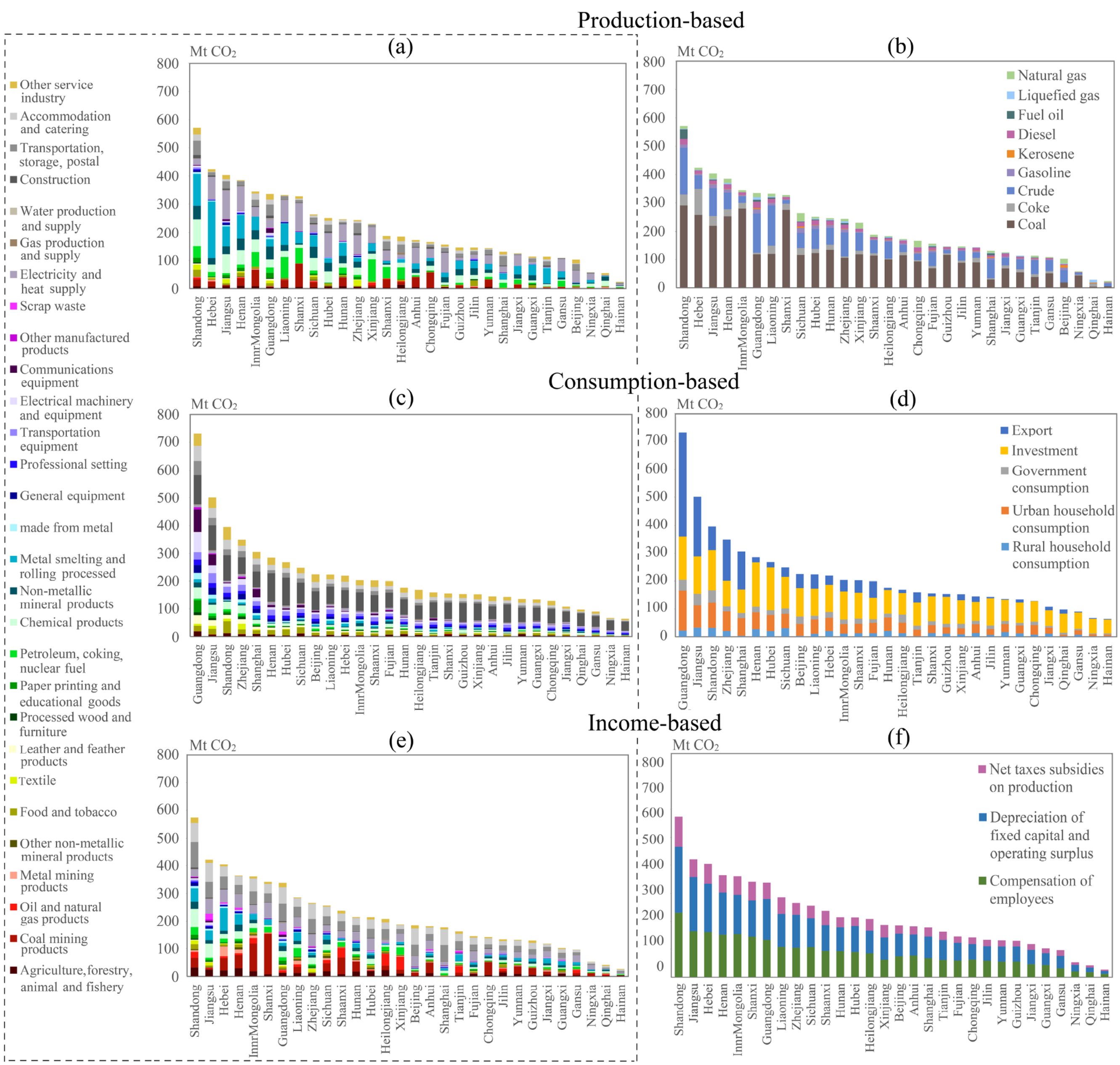

Fig. 1. CO_2 emissions of China's provinces in 2012. (a, c, e) Production-, consumption-, and income-based CO_2 emissions of all 29 sectors in 30 provinces. (b) Direct CO_2 emissions from different types of energy used by provinces. (d) CO_2 emissions embodied in various final demands consumed by provinces. (f) CO_2 emissions enabled by various primary inputs supplied by provinces.

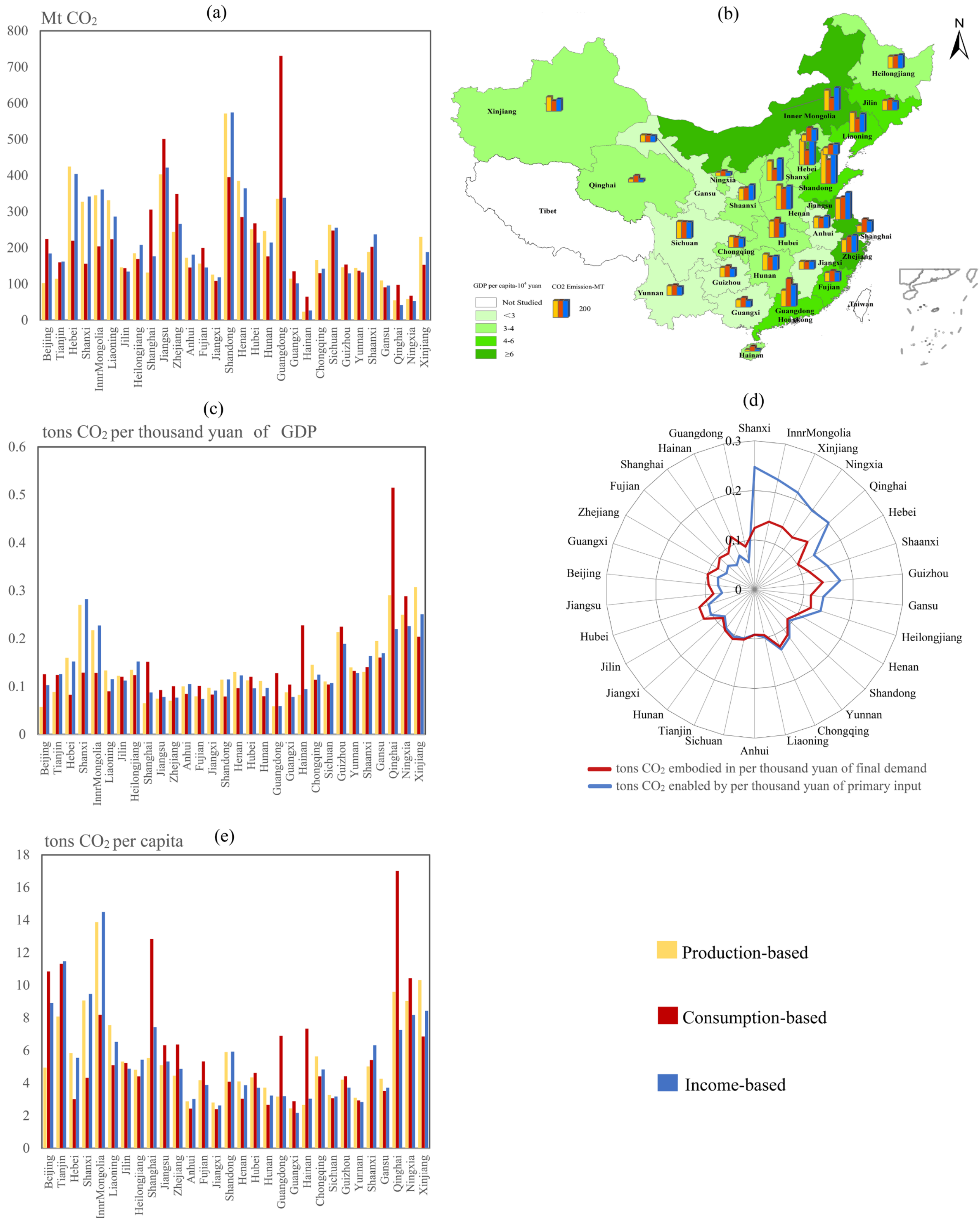

Fig. 2. Comparison of production-, consumption-, and income-based CO_2 emissions for provinces. (a, c, e) CO_2 emissions, CO_2 emissions per thousand yuan of GDP, and CO_2 emissions per capita of provinces, respectively. (b) Comparison of per capita GDP and CO_2 emissions. (d) Comparison of CO_2 emissions embodied in per thousand yuan of final demand and CO_2 emissions enabled by per thousand yuan of primary input.

emissions than their producers, such as Guangdong, Jiangsu, Zhejiang, Shanghai, and Beijing. Moreover, these provinces, which are mostly located in the south of China, must have imported large amounts of embodied emissions from other provinces to meet their final demand. For example, Guangdong only emitted 335 million tons CO_2 emissions (production-based) in 2012, but more than double (731 million tons) were emitted by other provinces in China to meet Guangdong's final demand. For this reason, Guangdong, as well as other provinces that have relatively high consumption-based CO_2 emissions, need to conduct more demand-side emission reduction policies (e.g., taxing the consumption and international exports of carbon-intensive products, encouraging low-carbon lifestyles, and reducing investment in real estate). Results at the sector level show that *Construction* has the largest consumption-based CO_2 emissions, 29% of China's emissions are driven by consumption and investment in the *Construction* sector. Mainly because building materials such as rebars and cement are carbon-intensive products. In addition, investment activities related to the *Construction* sector are also the main drivers of China's CO_2 emissions, the consumption-based CO_2 emissions of investment account for 43% of the national total emissions (Fig. 1d). By contrast; 14% of China's CO_2 emissions or 59% of its exported CO_2 emissions are embodied in the international exports of four southeast coastal provinces: Guangdong, Jiangsu, Zhejiang, and Shanghai. In terms of household consumption, the consumption-based CO_2 emissions of urban and rural households are 1256 million tons and 412 million tons, respectively. It is worth noting that in China, the urban and rural population sizes are similar, being 53% and 47%, respectively [51]. That is, the per capita consumption-based CO_2 emissions of urban residents is about triple that of rural residents. Therefore, the rural residents cannot completely imitate the lifestyle of urban residents in the process of urbanization, and the urban residents should also move to low-carbon consumption.

3.3. Analysis of China's provincial income-based CO_2 emissions

Fig. 1e and f present the income-based CO_2 emissions for provinces, the results show that the primary inputs of Shandong, Jiangsu, Hebei, Henan, Inner Mongolia, Shanxi, Guangdong and Liaoning enabled large amounts of CO_2 emissions, with a total of 3092 million tons of income-based CO_2 emissions, accounting for 47% of China's total emissions in 2012. These regions are located in northern China except Jiangsu and Guangdong, and include China's major energy resource-abundant provinces such as Shandong, Shanxi, Henan, and Inner Mongolia. Coal or oil extracted in these provinces will cause a lot of CO_2 emissions when they are used in downstream sectors and provinces. As a result, sectors related to resource extraction or energy supply such as *Coal mining products and Electricity and heat supply* also have large amounts of income-based CO_2 emissions. The CO_2 emissions enabled by the primary inputs of *Coal mining products and Electricity and heat supply* are 756 million tons and 784 million tons, or 11% and 12% of total emissions, respectively. These results indicate that supply-side emission reduction policies should pay more attention to energy resource-abundant provinces and energy-related sectors. However, what is more concerning is that tertiary industry sectors, which are generally regarded as low-carbon industries, are the major contributors to China's income-based CO_2 emissions. The primary inputs of the two tertiary sectors-*Transportation, storage, postal* and *Accommodation and catering* enabled 927 million tons and 910 million tons of downstream CO_2 emissions in 2012. This may reflect that China's tertiary industries are closely linked to carbon-intensive industries or provide a lot of services to carbon-intensive industries. Conversely, there are also big differences in sectoral income-based CO_2 emissions among provinces. For example, Guangdong and Henan have similar income-based CO_2 emissions, but the income-based CO_2 emission of their tertiary industry sectors accounted for 41% and 18% of their total income-based CO_2 emissions, respectively. This means that Guangdong's investment of labor resource and fixed assets in the Tertiary industry is much higher than that of Henan.

3.4. Comparison of China's provincial production-, consumption-, income-based CO_2 emissions

We further compare production-, consumption-, and income-based CO_2 emissions for each province in Fig. 2, as well as the CO_2 emission per thousand-yuan of GDP and CO_2 emission per capita. In Hebei, Shanxi, Inner Mongolia, Liaoning and Shandong, the production- and income-based CO_2 emissions are significantly higher than the consumption-based CO_2 emissions (Fig. 2a). This may suggest that, these provinces undertake the upstream carbon-intensive domestic production division (production-based), and produce a large amount of fossil energy, resulting in high downstream carbon emissions (income-based). In contrast, in coastal developed regions such as Beijing, Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, and in less developed western regions such as Guangxi, Guizhou, Qinghai and Ningxia, the consumption-based CO_2 emissions are higher than the production- and income-based CO_2 emissions, indicating that their emission reduction policies should pay more attention to the demand side.

China's less developed provinces such as Hainan, Qinghai, Ningxia, and Xinjiang have significantly higher consumption-based CO_2 emissions per thousand-yuan of GDP and higher consumption-based CO_2 emissions per capita than other provinces (Fig. 2c and e). This means these regions consume a higher proportion of carbon-intensive products or more final products consumed in these regions are from low carbon efficiency regions. Therefore, these provinces need to make efforts to reduce the consumption-based CO_2 emissions in future economic development.

It can be seen from Fig. 2b that regions with high per capita GDP (in dark green) can be divided into two categories. The one includes regions with relatively high production-based and income-based CO_2 emissions, mainly located in northern China, such as Inner Mongolia, Liaoning, and Shandong. The other includes regions with relatively high consumption-based CO_2 emissions, mainly located in southern China, such as Guangdong, Fujian, Zhejiang, and Shanghai. This finding implies that more production-side and supply-side policies be implemented in northern China and more demand-side policies in southern China. In addition, consumption-, production-, and income-based CO_2 emissions in less developed western regions (in light green) such as Yunnan, Sichuan, Gansu, and Guizhou are very similar, which may indicate that these regions are relatively less involved in China's domestic production division.

Fig. 2d shows the CO_2 emissions embodied per thousand yuan of final demand and CO_2 emissions enabled by per thousand yuan of primary input for provinces. First, the differences in CO_2 emissions embodied in per thousand yuan of final demand among provinces are not obvious, but there are huge differences in the latter index among provinces. In Shanxi, Inner Mongolia, Xinjiang, Ningxia, and Qinghai, the CO_2 emissions enabled by per thousand yuan of primary input are more than 0.2 tons, indicating that the primary inputs in these regions are more supplied to carbon-intensive sectors, or large amounts of their intermediate products used by downstream regions are carbon-intensive products such as coal, electricity. In addition, for the provinces on the right half of the circle diagram (Shanxi to Liaoning), the CO_2 emissions enabled by per thousand yuan of primary input are higher than those embodied in per thousand yuan of final demand, so the emission reduction policies in these regions need to pay more attention to supply side, and in contrast, policies in provinces on the left half of the circle diagram (Anhui to Guangdong) need to focus on demand side.

3.5. Analysis of embodied CO_2 emission flows in China driven by final demand and enabled by primary input

According to Fig. 3a and c, the amounts of interprovincial embodied emission flows driven by final demand are much higher than those enabled by primary inputs (embodied flows shown in Fig. 3a and c are flows greater than 5 million tons). This is because embodied emission flows driven by final demand are the result of interprovincial trade in intermediate and final products, while embodied emission flows enabled by primary inputs are only the result of interprovincial trade in intermediate products. This is also reflected in Fig. 3b and d: 4125

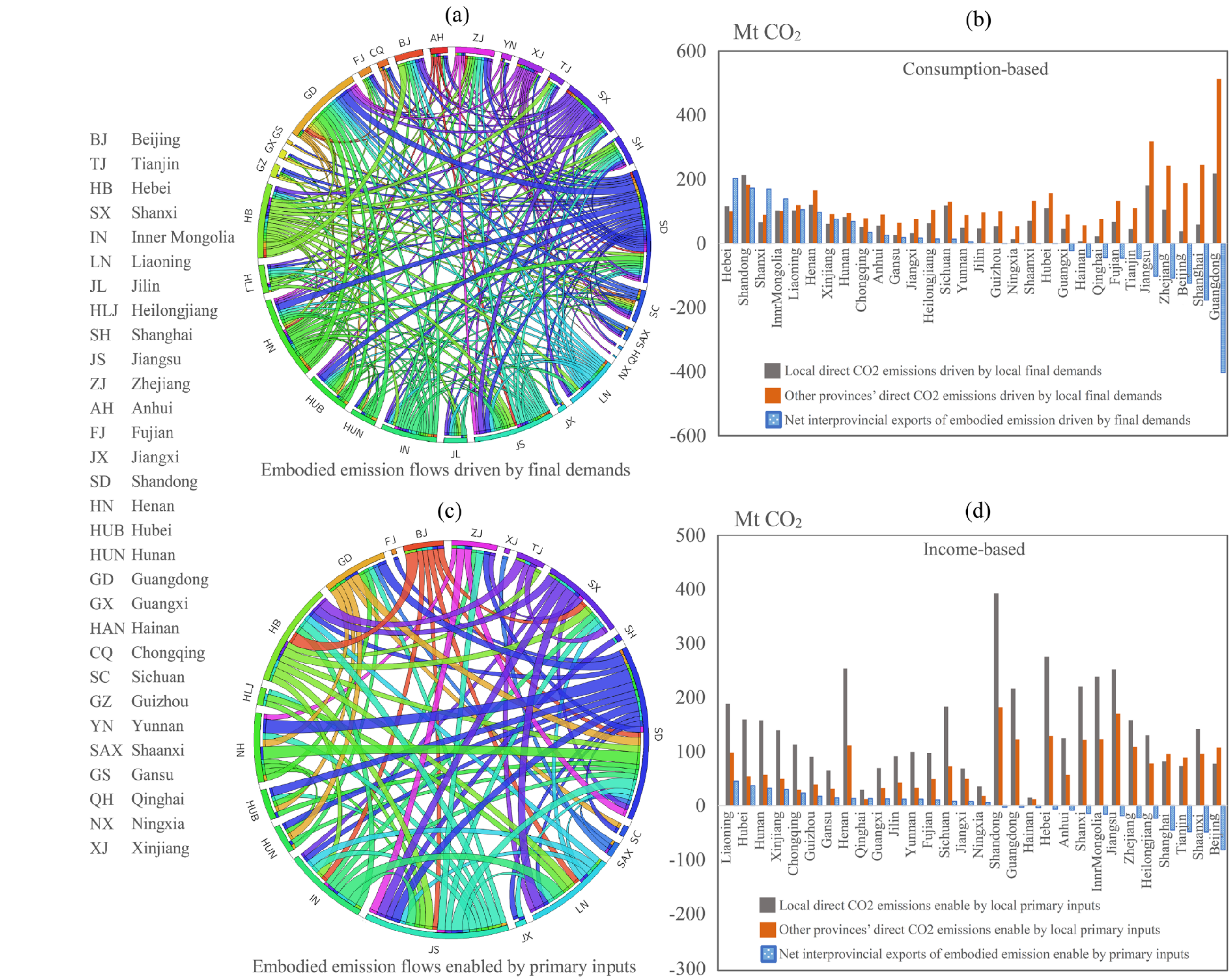

Fig. 3. Interprovincial embodied CO_2 emission flows in China. Interprovincial trade results in a large number of embodied CO_2 emission flows among provinces in China. The embodied flows can be driven by the final demands of provinces (consumption-based) through interprovincial import of intermediate and final products (a). As a result, the consumption-based CO_2 emission in each province include emissions embodied in local products and interprovincial imports (b). Similarly, the primary inputs of provinces can also enable embodied flows through interprovincial export of intermediate products and enable downstream CO_2 emissions (c). As a result, the income-based CO_2 emissions in each province also include two parts: the first is local direct emissions (production-based emissions) enabled by local primary inputs; the other is direct CO_2 emissions of other provinces enabled by local primary inputs (d). For provinces shown in a and c, the inner ring shows the embodied emissions imported from other provinces, and the middle ring shows the embodied emissions exported to other provinces.

million tons of CO_2 emissions are embodied in interprovincial trade to meet the final demands of provinces (red bars in Fig. 3b), while only 2265 million tons of CO_2 emissions are enabled by primary inputs and transferred among provinces (red bars in Fig. 3d), which means that for most provinces, their demand-side emission reduction policies have a greater effect on other provinces' emission than their supply-side policies. Thus, compared with supply-side policies, the provincial demand-side policies need other provinces to have more policy coordination at the production side. For example, if Guangdong introduces policies to reduce its consumption-based CO_2 emissions, the provinces who have exported large amounts of embodied emissions to Guangdong, such as Shandong, Henan, Hunan, and Hebei (Fig. 3a), also need more production-side reduction policies to reduce their direct emissions (production-based emissions).

Fig. 3b shows that the eastern coastal developed regions such as Guangdong, Shanghai, Beijing, Jiangsu, and Tianjin have imported large amounts of embodied emissions from Hebei, Shandong, Shanxi, Inner Mongolia, Liaoning, and Henan to meet their final demands. Therefore, these two types of provinces need to be aligned with demand- and production-side emission reduction policies, more specifically; the former regions need to introduce demand-side policies to reduce their consumption-based CO_2 emissions and the latter production-side policies to reduce their production-based CO_2 emissions. In this way, emissions reduction in China will be more efficient. Furthermore, we can see in Fig. 3c and d that the primary inputs of Beijing, Tianjin, Shanghai, Zhejiang, Heilongjiang, Shaanxi, Inner Mongolia, and Shanxi, which are eastern coastal developed regions or energy resource-rich regions, have enabled large amounts of CO_2 emissions to China's central and western inland provinces such as Hubei, Hunan, Xinjiang, Chongqing, Guizhou, and Gansu. Therefore, the provinces of the east and the west need to cooperate with emission reductions on supply- and production-side policies, respectively.

4. Discussion

At present, China is still ranked as a developing country. The China's government needs to maintain rapid economic development to minimize unemployment and eradicate poverty, while the domestic energy structure dominated by fossil energy and cannot be changed in the short term, which makes it particularly difficult for carbon mitigation in

China [52–54]. In fact, China's carbon emissions have increased with economic growth since the reform and opening up. Therefore, the economic factors affecting carbon emissions and their contribution to carbon emissions must be considered in the formulation of carbon mitigation policies. However, the increasingly convenient transportation and information services in China has led to complex inter-provincial trade networks in China, as well as complex inter-provincial emission flow networks. This poses many challenges to the formulation of emission reduction policies, especially how to achieve regional coordinated reduction.

For provinces in China, their production, demand and supply sides have different effects on China's carbon emissions, thus the emission mitigation policies in different provinces should be focused on different aspects. Therefore, we calculate the production-, consumption-, and income-based carbon emissions for provinces in China. Also, we clarify the contributions of different economic entities (producers, final consumers, and primary suppliers) to China's carbon emissions. Moreover, based on the comparison of the three kinds of emissions, we clarify the focus of each province's emission reduction policies. On the one hand, like many previous studies on China's carbon emissions accounting [55,56], our study highlights the roles of some heavy industrialized provinces in driving carbon emissions at the production side, such as Shandong, Hebei, Liaoning, and some developed eastern provinces in driving carbon emissions at the demand side, such as Guangdong, Shanghai, Zhejiang and Beijing. In addition, we found that although some provinces (e.g. Inner Mongolia and Shanxi) have relatively low direct emissions (production-based) and demand-driven emissions (consumption-based), but the primary inputs in those provinces have enabled a lot of downstream carbon emissions. The supply-side emission reduction policies needed by these provinces are often neglected by previous studies.

A large proportion of the previous studies on carbon emissions accounting focused on the division of emission reduction responsibilities. However, due to the differences in economic basis and development orientation of China's provinces, it is difficult for China to classify carbon emission reduction responsibilities based on provincial carbon emissions. What China needs is emission reduction policies that can achieve the overall emission reduction target. Usually, mitigation policies introduced in one province will not only affect local emissions, but also affect the emissions in other provinces. The complementary effects of policies between different provinces must be considered. Accounting for carbon emissions from different perspectives across the supply chain can help guide just and effective carbon reduction policies. This study also clarifies the roles of different provinces in inter-provincial embodied emission flow network from the upstream and downstream perspectives, which helps to formulate a coordinated plan for local and national emission reduction policies making. For example, we found that Hebei directly emits a large amount of carbon emissions, large amounts of its emissions are required by final demand in Beijing (Fig. 3a). Therefore, while Hebei roll out the emission reduction policies on production-side, Beijing also needs conduct supplementary support by implementing demand-side emission reduction policies. Similarly, large amounts of Hebei's emissions are enabled by primary input in Shanxi (Fig. 3c), which means Shanxi also needs induct supply-side policies to reduce its income-based emissions.

However, due to lack of data, this study failed to capture the trend of China's provincial carbon emissions after 2012. China's economy has entered a new phase, the so-called "New Normal". The role of international trade in China's economy have also undergone great changes. The impacts of this change on China's provincial carbon emissions and the policy implications of such kinds of change have not been analyzed in this study. Nowadays, the Chinese government is paying more attention to domestic demand and renewable energy. At the same time, it has proposed the concept of supply-side reform in recent years, and more supply-side policies have emerged. This will inevitably change China's provincial carbon emission pattern. Based on the limitations of this study, we will advance our work once there are updated data and carry out income-based emissions accounting at the city level.

5. Conclusions and policy implications

In this study, we analyze China's provincial production- consumption-, and income-based CO_2 emissions, to identify the main contributors of CO_2 emissions for provinces and to inform mitigation policies on the production-, demand-, and supply-side. Based on the results, some conclusions and policy implications can be summarized as follows:

(1) According to the results of provincial production-based CO_2 emissions, mitigation policies in provinces such as Shandong, Hebei, Inner Mongolia, Henan, Liaoning, and Shanxi, where the production activities directly emit larger amounts of CO_2, should be focused on production side. Specifically, more policies related to energy usage and industrial structure that aimed at reducing fossil energy use should be introduced in these regions. The central government should also reduce the dependence on fossil energy by developing renewable energy. Specifically, developing wind power in the southeastern coastal areas and the northwestern regions, solar energy in high-altitude provinces, such as Tibet and Qinghai, and biomass energy in some agricultural provinces, such as Heilongjiang, Sichuan, and Guangxi.

(2) According to the results of provincial consumption-based CO_2 emissions, provinces such as Guangdong, Jiangsu, Zhejiang, Shanghai have relative high consumption-based CO_2 emissions and consumption-based CO_2 emissions per capita. Large amounts of embodied CO_2 emissions are imported from north China to meet final demands in these provinces. Meanwhile, these provinces also export large amounts of CO_2 emissions to overseas. Therefore, the costal developed provinces should make efforts to reduce their consumption-based CO_2 emissions by introducing more demand side mitigation policies (e.g., encouraging low-carbon lifestyles by subsidizing low-carbon products, taxing on consumption and export of carbon-intensive products).

(3) According to the results of provincial income-based CO_2 emissions, the primary inputs of developed provinces (e.g., Guangdong, Jiangsu, and Zhejiang) and energy resource-abundant provinces (e.g., Shanxi, Shandong, and Inner Mongolia) have enabled large amounts of downstream CO_2 emissions. To reduce their income-based CO_2 emissions, the government can induce some supply-side policies to optimize the property rights structure in energy sectors, and reduce taxes, transaction costs and administrative barriers in the low-carbon sector so that more primary factors of production (e.g., labor forces, capital and government services) can be inputted to low carbon sectors, and the coal or oil companies in these regions can sell fossil fuels to more efficient regions. The government can also subsidize low-carbon technologies in sectors with high income-based emission.

(4) In addition, emissions reduction in the under-developed West of China also needs equal attention. According to our results, most of west provinces have high production-based CO_2 emission per unit of GDP, which is a dangerous signal for carbon reduction as the Chinese government is vigorously developing the western economy. If this situation cannot be improved, the western provinces will become the new main drivers of China's CO_2 emission growth in the near future.

(5) Our research also found that there is a big difference between urban and rural residents in CO_2 emission per capita in China. At present, the Chinese government is making efforts break down the dual urban-rural structure by expanding infrastructure investment in rural areas and advancing urbanization. However, previous studies have shown that urbanization is one of the main drivers of CO_2 emissions growth in China or even in the world [57–59]. As a result,

China will see hundreds of millions of its rural population turn into urban residents, unleashing increasing market demand, as well as emissions demand, which will inevitably bring huge pressure on national carbon emission reduction. Thus, the demand side policies for the reduction of consumption-based CO_2 emissions might be more necessary for China.

(6) Finally, from the perspective of the industrial sectors, the current carbon emission reduction policies are mainly concentrated in sectors with large amounts of direct emissions such as *Petroleum, coking and nuclear fuel, Metal smelting and rolling processed, Electricity, heat production and supply*. Therefore, the tertiary industries are often regarded as low carbon industries and supported by the government to help reduce emissions. However, we find that the tertiary industries are the main contributors to China's income-based CO_2 emissions, which means that the primary inputs of China's tertiary industry have enabled large amounts of downstream CO_2 emissions. For example, the tertiary industries of Guangdong province have contributed to 41% of its total income-based CO_2 emissions. For the whole country, the primary inputs of the tertiary industries have enabled 2026 million tons or 31% of total CO_2 emissions in 2012. This may be caused by the strong industrial relationship among industries in China. Thus, expanding the proportion of the tertiary industry without reducing its industrial linkages with carbon-intensive industries is not conducive to China's emission reduction.

Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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