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A R T I C L E I N F O

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A B S T R A C T

Cities are leading carbon mitigation but are heterogeneous in their mitigation policies due to different socio-economic backgrounds. Given that cities are increasingly inextricably linked, formulating mitigation policies of different cities cannot be easily achieved without comprehensive carbon inventories, who taking the inter-city supply chains into account. The Pearl River Basin is one of the important economic zones in China, with huge disparity in its cities, but very limited information is available on their consumption-based CO_2 emissions. To fill this gap, we compiled a consumption-based inventory of 47 cities in the Basin for 2012. We found that the total consumption-based emissions of 47 cities was 933.8 Mt, accounting for 13.1% of China's emissions. There were huge differences in the consumption-based emissions, ranging from 3.6 Mt (Heyuan City) to 153.1 Mt (Shenzhen City). The consumption-based emissions were highly concentrated in the largest seven cities, which accounted for 52.8% of the total emissions of the Basin. The consumption-based emissions per capita also varied greatly, from 1.2 to 14.5 tons per capita. Large scale infrastructure was the biggest driving force for most cities, resulting in 42.1% to 75.6% of the emissions. At sector-level, construction, heavy industry and services were leading in emissions, contributing more than 80% of emissions. The major inter-city carbon transfers occurred within upstream cities in the developing regions and downstream cities in the Pearl River Delta respectively, instead of the transfers between upstream and downstream cities. The findings highlight that the regional mitigation strategies could mainly focus on cities in intra-province boundary, rather than inter-province boundary, and also the city-level mitigation strategies should pay attention to the key emission sectors and drivers in respect of the heterogeneity of cities.

1. Introduction

Climate change has already become a major global challenge (Karl and Trenberth 2003), making carbon mitigation of the greatest importance to respond to the climate crisis (Ivanova et al., 2018). As the centers of economic and consumption activities, cities are home to more than half of the world's population, emitting more than three-quarters of the world's greenhouse gasses, and have come to have a key role to play in global decarbonization initiatives (Gouldson et al., 2016; Rosenzweig et al., 2010; Hallegatte and Corfee-Morlot 2010). Since 2008, China has become the global top emitter, and the mitigation in Chinese cities largely determines the success of the Paris 1.5° target (Wu et al., 2020; Mi et al., 2016; Mi et al., 2019; Zheng et al., 2019). However, Chinese cities have huge heterogeneity in terms of socioeconomic and demographic characteristics, such as industrial structure and affluence, which implies heterogeneous responsibility of cities and low carbon pathways in respect to those distinctions between them.

The Pearl River is the third largest river of China, flowing through six provinces (Dai et al., 2008). The GDP of all the Pearl River Basin cities in 2012 was 9.2 trillion RMB, accounting for 17.1% of China's GDP, and approximately equivalent to that of Spain and half that of France. Meanwhile, the developments for cities in the Basin are highly uneven.

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The downstream area of the Basin, the Pearl River Delta, is the most economically advanced region in China, while the upstream area is the less developed region of China. The nine cities of the Delta contributed 4.9 trillion RMB GDP together, accounting for 9.0% of the total GDP of 333 Chinese cities, which was approximately equivalent to that of Saudi Arabia, half that of Australia, and one third that of the United Kingdom in 2012. However, the total GDP of the cities in the Basin outside the Pearl River Delta amounted to 87.8% of the nine cities in the Delta. In recent years, the Chinese government has promulgated several economic coordinated development policies, such as the Development Planning for the Guangdong-Hong Kong-Macao Greater Bay Area, hoping to strengthen the infrastructure construction of roads and waterways between the downstream and upstream area, promote the trade exchanges, and ultimately narrow the economic gap between cities in the Basin.

To identify mitigation responsibility of cities, there are two approaches to calculate carbon dioxide emissions: the production-based emission inventory and the consumption-based emission inventory (Zhang and Lin 2018; Peters 2008; Fernández-Amador et al., 2017). The production-based emissions contain the carbon dioxide emitted by the producer during the production process (Homma et al., 2012; Wu et al., 2015). This method focuses on the production, regardless of who consumes the products (Zhou et al., 2018; Franzen and Mader 2018). The consumption-based emissions assign the responsibility for emitting carbon dioxide to the person who consumes the products (Millward-Hopkins et al., 2017; Steininger et al., 2018). Generally speaking, the production-based emissions for cities include the carbon dioxide emitted during the production of locally-consumed products and the products for export, but does not include the carbon dioxide emitted by imported products; while the consumption-based emissions include the carbon dioxide emitted during the production of locally-consumed products and imported products, but does not include the carbon dioxide emitted by exported products. Compared with the production-based emissions, the consumption-based emissions provide a perspective of consumption, taking the supply chain into consideration and thus enabling us to analyze the emission flow among industrial sectors and regions (Karakaya et al., 2019). With the consumption-based emission inventory, we can have a better understanding of the responsibility for emission reduction, and improve both impartiality and cost-effectiveness of the reduction activity (Steininger et al., 2014; Afionis et al., 2016).

However, understandings on consumption-based emissions are still mainly at national or regional level (Hertwich and Peters 2009; Wang et al., 2018; Liu et al., 2015), but more city-level studies of consumption-based emissions have emerged in recent years (Long and Yoshida 2018; Andrade et al., 2018; Zheng et al., 2019; Zhang et al., 2021), such as Xiamen (Vause et al., 2013), Brussels (Athanassiadis et al., 2018), Shanghai (Shao et al., 2020), and Hebei cities (Mi et al., 2019; Zheng et al., 2019). Despite these efforts, most of the cities are still uninvestigated. Among the current city-level studies, most of the studies were based on the SRIO (single region input-output) method, such as Hebei cities of China (Mi et al., 2019; Li et al., 2019), 79 global C40 cities (Wiedmann et al., 2021), and 16 global megacities (Chen et al., 2020). However, the studies based on the SRIO method cannot trace the supply chains with heterogeneity in producers, which could under- or over-estimate consumption-based emissions. To overcome the gap, the MRIO (multi-regional input-output) method has been increasingly applied as it can quantitatively track the carbon emissions embodied in the supply chains among cities (Zheng et al., 2019). But the studies are still scarce due to the unavailability of city-level MRIO tables. Zheng et al. (2019) compiled the first city-level MRIO table for Beijing-Tianjin-Hebei urban agglomeration and identified the unsustainable pattern of carbon flows transferred from the cities in Hebei Province to Beijing and Tianjin. Chen et al. (2016) constructed a global MRIO model to derive the carbon footprint of five megacities in China and five state capital cities in Australia, and pointed out that the coordination of emission reduction policies between China and Australia potentially had important benefits. Previous studies had a very limited coverage focusing on Pearl River cities, with the focus on discrete cities. For example, Dou et al. (2021) analyzed the carbon footprints of Hong Kong and Macao from 2000 to 2015. To our knowledge, there are no studies exploring the consumption-based emissions inventory for the Pearl River cities.

In this study, we constructed a city-level MRIO table of 47 cities of the Pearl River Basin and filled the gap in the consumption-based carbon emission inventory of the cities in the Pearl River Basin in 2012, and based on what we discovered about the carbon inequality of the cities. We measured the carbon inequality by using per capita consumption-based emissions, since it reflects the per capita expenditure level or living standard. The paper is organized as follows: in Section 2, we introduce the basics of MRIO model, the method of accounting for consumption-based emissions by MRIO table, the method for compiling the territory carbon emissions inventory, and the method for city-level MRIO table compilation. In Section 3, we display the consumption-based carbon emissions of the 47 cities in the Pearl River Basin and the carbon inequality among cites, along with their structure on driving factors and sectors, as well as the carbon transfers between cities in the Pearl River Basin. In Section 4, we discuss the results and illustrate our policy recommendations. Finally, we draw the conclusion in Section 5.

2. Method and data

2.1. Consumption-based emission accounting based on the multi-regional input-output method

Input-output (IO) analysis is a quantitative framework to analyze the interdependence of sectors in the economy, established by Wassily Leontief (1936, 1951). This method has been extensively used on environmental issues associated with economic activity (Wiedmann 2009), such as energy consumption (Cellura et al., 2013; Wei et al., 2015), resource use (Cazcarro et al., 2013; Wiedmann et al., 2015; Ewing et al., 2012; Weinzettel et al., 2013), greenhouse gas emission (Yan et al., 2016; Ali et al., 2018), air pollution (Yang et al., 2016; Lin et al., 2014), and biodiversity loss (Lenzen and Murray 2001; Lenzen et al., 2012). It provides a quantitative approach to trace the environmental impacts along the supply chains. The multi-regional input-output analysis is developed on the basis of IO analysis and contains the information on inter-regional trade in the supply chains. The MRIO has been widely applied in calculating consumption-based emissions and tracking carbon flows generated out of the boundary (Shao et al., 2018; Feng et al., 2014).

As shown in Table 1, a MRIO table comprises a data set of the transactions between the supplying sector and the using sector from the same or different regions (both intraregional transactions $\mathbf{Z}^{rr}, \mathbf{Z}^{ss}$ and interregional transactions $\mathbf{Z}^{rs}$, $\mathbf{Z}^{sr}$) and final demand, value added, import, export and gross output of each sector in each region. The superscripts denote regions, and the sequence of superscripts represents the direction of value flow.

With a MRIO table, which is constituted of m regions and n sectors in each of these regions, the basic mathematical formula of the MRIO is:

$$\begin{pmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{pmatrix} = \begin{pmatrix} a^{11} & a^{12} & \cdots & a^{1m} \\ a^{21} & a^{22} & \cdots & a^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a^{m1} & a^{m2} & \cdots & a^{mm} \end{pmatrix} \begin{pmatrix} x^1 \\ x^1 \\ \vdots \\ x^m \end{pmatrix} + \begin{pmatrix} \sum_r f^{1r} \\ \sum_r f^{2r} \\ \vdots \\ \sum_r f^{mr} \end{pmatrix} \tag{1}$$

Or simplified as:

$$\mathbf{X} = \mathbf{AX} + \mathbf{F} \tag{2}$$

The gross output column vector $\mathbf{X}$ consists sub-vectors x^r, whose elements $[x_i^r]$ is the total output of region r's sector i, where the subscripts

Table 1
A two-region multi-regional input-output table.

		Intermediate demand		Final demand		Exports	Gross output
		Region r	Region s	Region r	Region s		
Intermediate input	Region r	$\mathbf{Z}^{rr}$	$\mathbf{Z}^{rs}$	$\mathbf{f}^{rr}$	$\mathbf{f}^{rs}$	$\mathbf{e}^{r}$	$\mathbf{x}^{r}$
	Region s	$\mathbf{Z}^{sr}$	$\mathbf{Z}^{ss}$	$\mathbf{f}^{sr}$	$\mathbf{f}^{ss}$	$\mathbf{e}^{s}$	$\mathbf{x}^{s}$
Value added		$\mathbf{v}^{r}$	$\mathbf{v}^{s}$				
Imports		$\mathbf{m}^{r}$	$\mathbf{m}^{s}$				
Gross input		$\mathbf{x}^{r}$	$\mathbf{x}^{s}$				

denote a specific sector. The technical coefficient matrix **A** consists of sub-matrices a^{rs}, whose elements $[a_{ij}^{rs}]$ is defined as $[a_{ij}^{rs}] = z_{ij}^{rs} / x_j^s$, where the sequence of subscripts represents the direction of flow, z_{ij}^{rs} is the monetary value transaction from sector *i* of region *r* to sector *j* of region *s*, x_j^s is the total output of sector *j* in region *s*. The elements of final demand column vector **F**, $\sum_R f^{lr}$, are the summations of final demand supplying from region *l* to all regions in the model.

Consolidating **X**, and reorganizing the formula:

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

where **I** is the identity matrix, and **L** is called Leontief inverse matrix (Wu and Liu 2016).

Supposing there is a row vector **D**, each of its elements, $[d_i^r]$, represents the direct carbon emission intensity of the sector *i* in region *r*, that is, the production-based emissions of the sector *i* in region *r* divided by the total output of this sector. Apparently

$$t = \mathbf{DX} \tag{4}$$

where t is the total carbon dioxide emissions.

Combining the formula (3) and (4):

$$t = \mathbf{DLF} \tag{5}$$

Evidently, t is a scalar, which is the summation of the carbon emissions of every sector in the whole area that we are concerned with. We can attain the meaningful intermediate results of the matrix operations by diagonalizing the row or column vectors of one end or both ends.

$$\mathbf{T} = \mathrm{diag}(\mathbf{D})\mathbf{L}\mathrm{diag}(\mathbf{F}) \tag{6}$$

where **T** denotes the matrix whose elements represent the emissions from one producer sector of a region to another sector of the same or different region, diag(**F**) means the diagonalized matrix of vector **F**.

$$\mathbf{T}_c = \mathbf{DL}\mathrm{diag}(\mathbf{F}) \tag{7}$$

where $\mathbf{T_c}$ is a row vector, the element of which represents the consumption-based emissions of each sector. By calculating with the above formulas, we can acquire the consumption-based emission inventory.

2.2. Territory carbon emission inventory compilation

Territory carbon emission inventory is the calculation basis of the consumption-based emission inventory, because in order to get the vector **D** in formula (7), the territory carbon emission inventory is prerequisite. The territory inventory compiling process we used is based on the mass-balance theory, following the definition of the emission accounting approach of the Intergovernmental Panel on Climate Change (IPCC), with the emissions calculated by multiplying the activity data and emission factors. Two different types of territory emissions - fossil fuel-related emissions and process-related emissions - were distinguished in the compiling method (Shan et al., 2017; Shan et al., 2018).

The fossil fuel-related emissions refer to the emissions caused by the burning of fossil fuels.

$$CE_{ij} = \sum_i \sum_j AD_{ij} \times NCV_i \times CC_i \times O_{ij} \tag{8}$$

where CE_{ij} is the carbon dioxide emissions caused by the sector *j* through the use of the fossil fuel type *i*, AD_{ij} is the corresponding fossil fuel amount. NCV_i, CC_i and O_{ij} are all emission factors of the fossil fuel type *i*, where NCV_i (net calorific value) denotes the heat value released during the burning of per unit of fossil fuel, CC_i (carbon content) denotes the carbon dioxide emissions of per heat value, O_{ij} (oxygenation efficiency) refers to the oxidation rate in the combustion process of the sector *j*.

The process-related emissions refer to the emissions escaping from chemical reactions in the industrial processes.

$$CE_t = AD_t \times EF_t \tag{9}$$

where CE_t is the carbon dioxide emissions induced in the industrial processes *t*, AD_t refers to the production amount of processes *t*, EF_t denotes the emission factor. And finally, the territory carbon emissions are the sum of CE_{ij} and CE_t.

2.3. City-level MRIO table compilation

The MRIO table is another calculation basis for consumption-based emission inventory, who provides **L** and **F** in formula (7). Since China does not publish city-level MRIO tables or even SRIO tables, in this study, we constructed a city-level MRIO table under the entropy-based framework developed by our previous works (Zheng et al., 2020; Zheng et al., 2021). This framework first constructs a city-level MRIO table for each single province, and then obtains the city-level MRIO table of China by nesting the city-level MRIO tables of the provinces into the provincial MRIO table of China (Zheng et al., 2019).

The compilation process starts with the estimation of domestic supply and demand of a specific sector *i* at city-level. For sector *i*, the domestic supply of a city means *i*'s output excluding its exports. The domestic demand of a city means all *i*'s products that are produced in China and are consumed in the city. The supply can be calculated by officially published data and the demand can be estimated from the provincial IO table based on some necessary assumptions. After that, the domestic supply can be further broken down into the supply to the local city (SL), the supply to other cities in the province (SP), and the supply to cities outside the province (SO). Similarly, the domestic demand can be further broken down into the demand from the local city (DL), the demand from other cities in the province (DP), and the demand from cities outside the province (DO). There are quantitative relationships between these decomposed variables. For example, the SL and DL of each city are equal, and the sum of SP of all cities in the province are same as the sum of DP. The quantitative relationships are used as constraints to estimate the most unbiased estimation of these variables for all cities in a province with the help of maximum entropy model. These variables are the basis for compiling the MRIO table.

A preliminary estimate of the city's intermediate demand matrix (i.e. the intraregional transactions $\mathbf{Z}^{rr}$ in table 1) can be obtained by multiplying the provincial technical coefficients by the city's total output, and a preliminary estimate of the city's final demand matrix can be obtained by subtracting the city's net exports (exports minus imports) from the city's value added. The preliminary matrices do not satisfy the quantitative relationship contained in the IO table. For example, the summation of the intermediate demand, the final demand and the net exports of each row should be equal to the output. These quantitative relationships are used as constraints to obtain the city's competitive IO table with the help of the frequently-used RAS method. Assuming a fixed proportion of imports and inflows in intermediate and final demand, the city's non-competitive IO table can be derived. In this process, the import IO table of the city is also produced, which is the aggregation of the inflow from other cities in the province, the inflow from other cities outside the province, and the foreign import. The non-competitive IO tables are the diagonal elements in the city-level MRIO table, and the import IO tables will be further divided to estimate the non-diagonal elements in the next step.

SPs and DPs are the total amounts of trade between cities, which are the constraints of the sum of inter-city trades. With the help of maximum entropy model, the inter-city trades between every pair of cities can be evaluated under the constraints. Then the inflow purchase coefficients matrix of each sector should be constructed, whose elements are the proportion of the inter-city demand which is supplied by other cities. Multiply the intermediate demand matrix and final demand matrix of the import IO tables with the inflow purchase coefficients matrices will obtain the data on the flow between cities of each sector, which are organized as the off-diagonal elements in the MRIO table. Supplement imports, exports, value-added and total output into the table at the appointed position, will create a complete city-level MRIO table of a province. Finally, after obtaining the city-level MRIO tables of some provinces, they can be nested into the provincial MRIO table of China. The details of the compiling framework can be found in Zheng et al., 2020; Zheng et al., 2021.

2.4. Data source

We used a territory carbon dioxide emission inventory in 2012 derived from the China Emission Accounts and Datasets (CEADs) (Shan et al., 2017; Shan et al., 2018; Shan et al., 2019). The inventory covered 42 sectors, which corresponded to the MRIO table. The list of these 42 sectors is shown in Appendix.

Although our study focused on 47 cities of the Pearl River Basin, the supply chains of Pearl River cities are often out of the Pearl River Basin (Zhang et al., 2020). For example, Guangzhou City may have products imported from Beijing, while the production in Beijing may require the goods or services from Shenzhen City. In order to trace the full supply chains in China, we constructed a 95-region MRIO with 42 sectors in each region under the entropy-based framework introduced above. The 95 regions included 47 cities of the Pearl River Basin in Guizhou, Guangxi, Guangdong, Jiangxi, Hunan Province, and all the other 48 cities or provinces of China, except for Hong Kong, Macao and Taiwan. In addition, in our MRIO table, Yunnan Province, 5 cities of which are located in the Basin, appeared as a whole region, because of the lack of data for the cities of Yunnan. As a result, only 47 of the 52 cities in the Pearl River Basin can be analyzed. In the compilation process, the city's import and export data were obtained from the China Customs Database; the value added and total output of each sector of the cities were obtained from the City Statistics Yearbook; the provincial IO tables were issued by provincial statistical bureaus. Excluding import and export trade, we only considered the supply chains within the 95 regions (i.e. the supply chains within China). Therefore, the import and export mentioned in this paper refers to the domestic import and domestic export.

3. Result

3.1. Carbon inequality of cities in the pearl river basin

In 2012, the total amount of the consumption-based emissions of the 47 cities of the Pearl River Basin was 933.8 Mt (million tons), accounting for 13.1% of the whole country (**Fig. 1a**). This ratio was lower than the proportion of the population and GDP of these 47 cities in the country, 15.9% and 15.4% respectively. The consumption-based emissions per capita (4.5 tons per capita) and per unit of GDP (11,028.2 tons per 100 million RMB GDP) in this region were both lower than the national average (5.5 tons per capita and 12,402.5 tons per 100 million RMB GDP). The Pearl River Delta, located downstream of the river and containing nine prosperous cities - which are Guangzhou, Foshan, Zhaoqing, Shenzhen, Dongguan, Huizhou, Zhuhai, Zhongshan and Jiangmen - was the district with the highest concentration of consumption-based emissions in the Basin, contributing 453.4 Mt emissions. With 24.5% of the total population in the Basin, these nine cities contributed 52.7% of GDP and emitted 48.6% emissions of the entire Basin. The other 38 cities emitted 51.4% emissions of the Basin, which was only 2.8% more than these nine cities.

Consumption-based emissions were highly distinct among the cites, from the largest, 153.1 Mt for Shenzhen City, to the smallest, 3.6 Mt for Heyuan City, where the difference was more than 40 times. This difference was the result of multiple factors, such as economy, population, technology, and consumption habits, etc. Shenzhen's population was 3.5 times that of Heyuan, and Shenzhen's GDP was 21.9 times that of Heyuan. The seven cities with the largest consumption-based emissions in the region were shown in **Fig. 1a**, and again confirmed that the major emissions were emitted in only a few cities. These seven cities emitted 493.4 Mt, taking up 52.8% of those for the whole Basin, however, the population and GDP ratio was 25.9% and 52.2%. Four of these cities, Shenzhen, Guangzhou, Dongguan and Foshan, all belonging to the Pearl River Delta, happened to be the four cities with the largest GDP and they emitted 372.1 Mt carbon dioxide, accounting for 39.8% of the Basin's emissions. It is worth noting that all provincial capital cities in the Basin - Guangzhou, Nanning and Guiyang–were listed, which illustrates the central position of provincial capital cities in the formulation of carbon emission reduction policies. Liuzhou City was a heavy industry city, where the output value of automobile, metallurgy and machinery accounted for 67.5% of the total industrial output value. And with GDP increasing by 11.5% in 2012 compared to 2011, Liuzhou had the second fastest growth rate among 24 cites which had more than 100 billion RMB GDP, with the first position occupied by a provincial capital city, Guiyang.

Consumption-based emissions per capita varied greatly among cities (**Fig. 1b**). The largest was Shenzhen (14.5 tons per capita), and the smallest was Heyuan (1.2 tons per capita). The difference between these two cities was 12.1 times. Three reasons together induced this difference: the consumption per capita, the local consumption structure, and the source structure of consumed goods or services. In Shenzhen, the consumption per capita was 156,133 yuan, of which 12.0% (18,676 yuan) was spent in the Construction sector, and 8.8% (13,765 yuan) was spent in the Manufacture of Electrical Machinery and Apparatus sector. While in Heyuan, the consumption per capita was 11,825 yuan, only 7.6% of Shenzhen, of which 27.2% (3217 yuan) was spent in the Construction sector, and 8.1% (957 yuan) was spent in the Farming, Forestry, Animal Production and Fishery sector. In addition, the producing areas of the commodities they bought were different, and the emissions of the same product produced in different places are not the same, because of the discrepancy on technique level, energy structure, etc. Besides this, among these cities, the high emissions per capita of a city did not mean that its emission intensity per unit of GDP was high

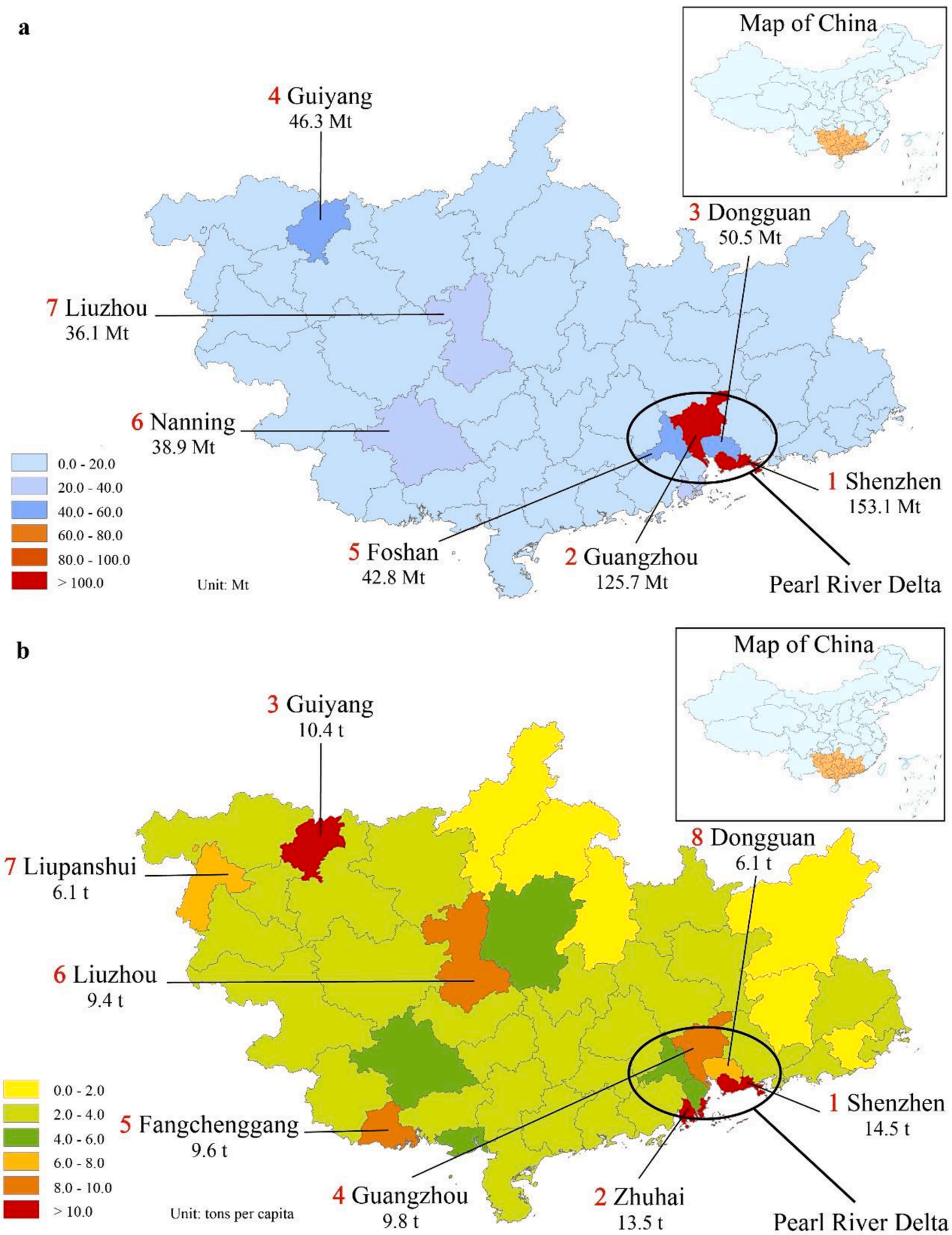

Fig. 1. a. Consumption-based emissions of 47 cities in the five provinces of the Pearl River Basin; b. Consumption-based emissions per capita of 47 cities in the five provinces of the Pearl River Basin.

either. There is no obvious relationship between these two variables. For example, the city with the largest emissions per capita, Shenzhen, ranked 19th among these 47 cities in terms of emissions per unit of GDP.

3.2. Consumption-based emission structure of cities in the pearl river basin by driving factors and sectors

Fig. 2 shows the consumption-based emission structure of 47 cities in the Basin by five driving factors, and highlights seven major cities. Fixed capital formation was the biggest single contributor for most cities, ranging from 42.1% to 75.6%. Fixed capital formation refers to the total value of fixed capital acquired by resident units within a certain period of time minus the total value of fixed capital disposed of, where the fixed capital is produced through production activities and has a useful life of more than one year and a unit value above the prescribed standard, excluding natural assets. Fixed capital formation contributed 42.6% of Shenzhen City's emissions, 49.5% of Guangzhou, 72.1% of Nanning and 67.9% of Guiyang. This result ties in with some former researches on Chinese emission driving forces, where Guan et al. found capital formation was one of the main driving forces in China from 2002 to 2005 and Feng et al. found capital formation was the key contributor in the Eastern-Coastal, Central and Western economic zones of China (Guan et al., 2009; Feng et al., 2012). The high contribution of the fixed capital formation to the emissions was the consequence of the urbanization process (Mi et al., 2016; Minx et al., 2013). Urban household consumption was the second biggest single contributor for most cities, ranging from 11.7% to 48.8% - 48.8% of Shenzhen City, 37.2% of Guangzhou, 14.3% of Nanning and 17.5% of Guiyang's

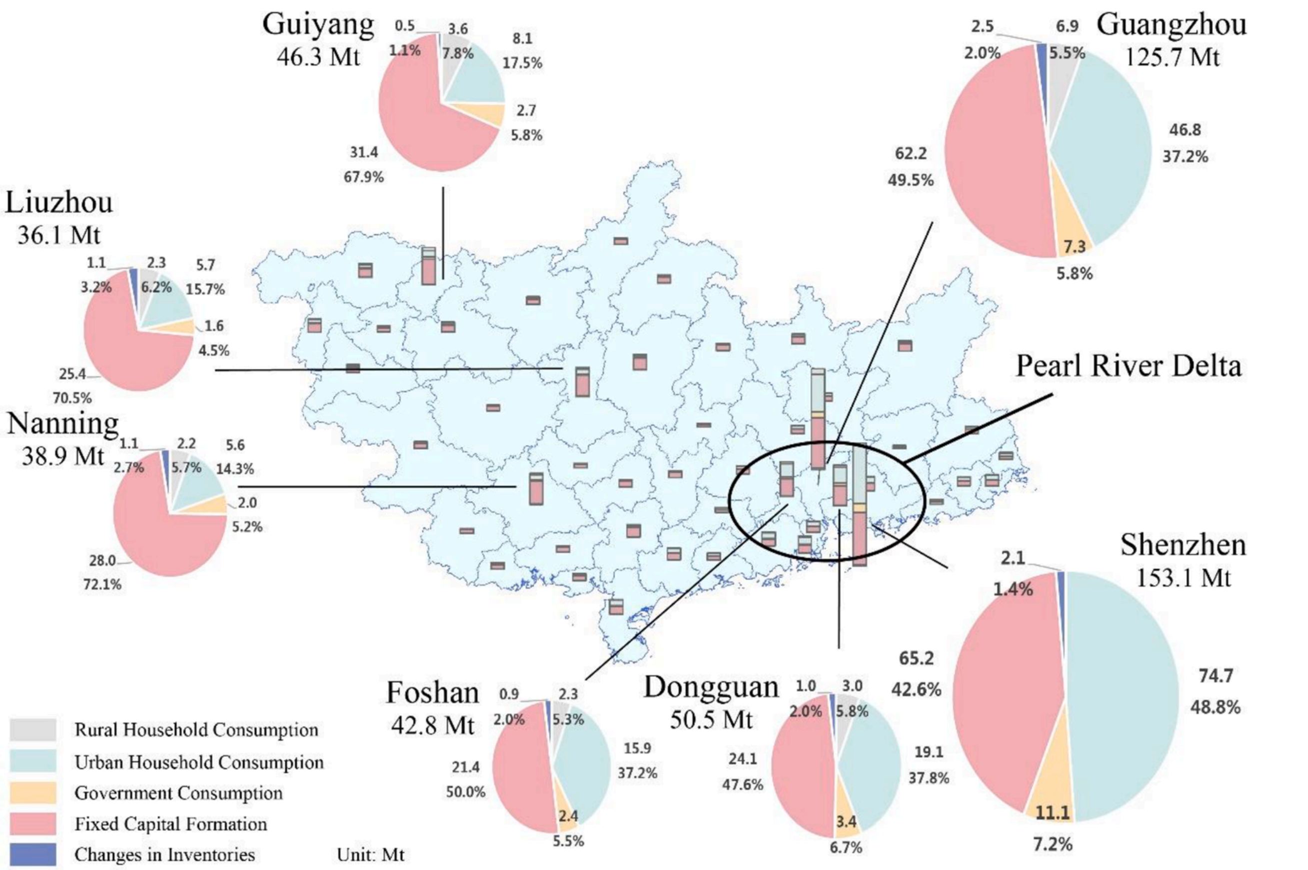

Fig. 2. The consumption-based emission structure by driving factors of 47 cities in the five provinces of the Pearl River Basin. It should be noted that these five driving factors are also the final demand classification method selected by the National Bureau of Statistics of China when compiling the national IO table. This classification was continued in our compilation and analysis process.

consumption-based emissions were caused by urban household consumption. From the beginning of the Economic Reform in 1978 to 2012, China's urban population increased by more than 60 million people, as the proportion of the urban population increased from less than 20% to more than 50%. The substantial increase in the urban population was an important reason for the increase in carbon emissions caused by urban household consumption. In addition, the urbanization rate also affects the consumption capacity of urban-rural populations. In cities with high urbanization rate, the difference between the expenditures per capita of urban residents and rural residents in final demand tends to be smaller. The urban and rural expenditures on final demand in Guangzhou, whose urbanization rate was 85.0%, were 46,133.5 and 41,838.4 yuan per capita respectively. The expenditures in Qianxinan, whose urbanization rate was 32.0%, were 7670.8 and 1874.4 yuan respectively.

The nine cities in the Pearl River Delta and the cities within the same province showed a roughly equivalent pattern of consumption-driven (rural household, urban household and government consumption) and investment-driven (fixed capital formation and changes in inventories) emissions. Some 44.0% of Shenzhen City's 153.1 Mt were caused by investment, and 51.5% of Guangzhou's 125.7 Mt, 50.4% of Dongguan's 50.5 Mt resulted from investment. However, for cities in other provinces in the Basin, investment-driven were distinctly stronger than consumption-driven emissions. The consumption-based emissions driven by investment in other cities ranged from 61.6% to 78.0%. In Nanning, Guiyang and Liuzhou, 74.8%, 69.0% and 73.6% were driven by investment. It is generally believed that the higher the urbanization rate, the lower the proportion of fixed capital formation in final demand. The national average urbanization rate of China in 2012 was 52.6%, while this index in the province where the Pearl River Delta is located was 67.4%. As the urbanization rate increases, the contribution of fixed capital formation to carbon emissions will decrease, and the contribution of household consumption will increase. The urbanization rate of other provinces in the Basin were much lower than the national average, from 36.4% to 47.5%, and therefore the urbanization of these cities still had room for improvement and required the formation of fixed capital.

In order to analyze the emission structure by sectors more conveniently and to explain more clearly, the initial 42 sectors were merged into 8 sectors. The merging plan is shown in the Appendix. Fig. 3 shows the emissions from various sectors of consumption-perspective of 21 typical cities in the region (nine cities with consumption-based emissions of more than 20 Mt; four cities with production-based emissions of more than 20 Mt; three cities with net value of emissions, which means production-based emissions minus consumption-based emissions, of more than positive 6.0 Mt; and four cities with net value of emissions of less than negative 6.0 Mt. Some cities belonged to different types at the same time). Seven of these cities belong to the Pearl River Delta, and the other 14 cities do not. In most cities, construction, heavy industry and the service sector were the most important sectors of consumption-based emissions, ranging from 11.9% to 65.8%, from 5.3% to 64.4%, from 8.2% to 60.5% of the total, respectively. The consumption-based emissions of all 21 typical cities were highly concentrated in these three aggregated sectors, accounting from 66.3% to 93.3%, and averaged more than 80%. These sectors contributed 47.1 Mt or 87.1% of Shenzhen's consumption-based emissions, 89.9 Mt or 85.3% of Guangzhou and 49.6 Mt or 93.3% of Guiyang.

Consumption-based carbon emissions per capita in various sectors also showed differences. In the construction sector, Guiyang emitted 7.9 tons of carbon dioxide per capita, and Bijie emitted 0.1 tons per capita. In the heavy industry sector, Foshan emitted 6.1 tons of carbon dioxide per capita, and Qianxinan emitted 0.1 tons. In the service industry

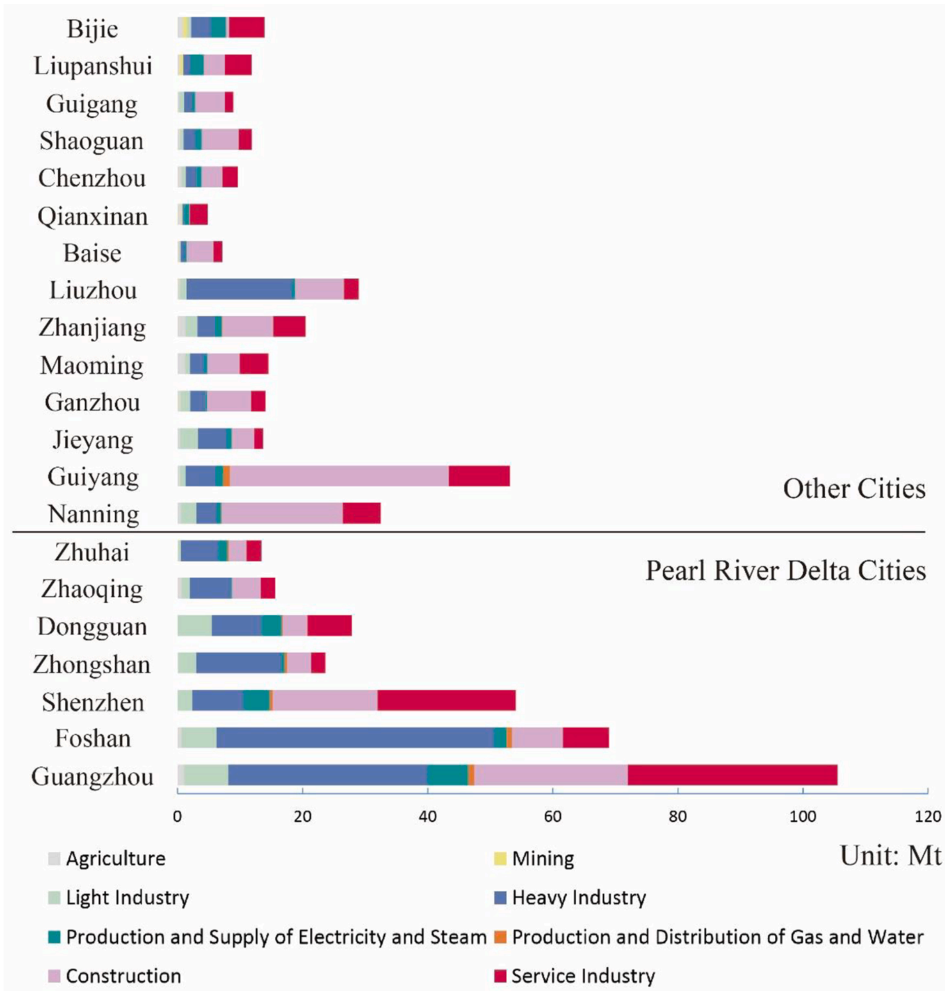

Fig. 3. The consumption-based emission structure by sectors of 21 typical cities.

sector, Guangzhou emitted 2.6 tons of carbon dioxide per capita, and Jieyang emitted 0.24 tons. The main reasons for the inequality in consumption-based carbon emissions per capita were the difference in ability to consume and the technical level of the production area of the goods or services these cities bought from. We have observed that there was no great difference in the per capita consumption structure of these cities. Guiyang spent 31.5% on the construction sector per capita, and Bijie was 27.6%. Foshan spent 26.8% on the heavy industry sector per capita, and Qianxinan was 13.7%. Guangzhou spent 38.8% on the service industry sector per capita on average, and Jieyang was 35.4%. Therefore, the consumption structure cannot explain why there was such big inequality. The difference of the ability to consume among these cities partly explained the phenomenon, where the annual per capita consumption in Guangzhou was more than 170,000 yuan, and the per capita consumption in Bijie was about 10,000 yuan. The remaining inequality was caused by the different emissions of the commodity of each sector when it was produced in different cities.

3.3. *Carbon flows within the cities of the pearl river basin*

About 52.1% of the total consumption-based emissions of all 47 cities flowed in from cities outside the Basin, which illustrates the importance of using the perspective of the consumer to look at the city-level emissions. The amounts of transfers within the Basin accounted for 40.7% of the total inflows of the 47 cities, which demonstrated that the emission interdependence between these cities in the Basin were strong. Different cities varied greatly in their dependence on other cities in the Basin. The proportion of imported carbon from other cities in the Basin to total consumption-based emissions ranged from 4.8% to 56.9%. The cities with particularly low dependence were mainly located on the northern border of the Basin, while the cities with particularly high dependence were mostly cities with small economic volume. 56.9% of Anshun's consumption-based emissions came from the other cities in the Basin, and Anshun's GDP, about 1 in 37 of Guangzhou's GDP, ranked bottom of the 47 cities. Hezhou, which ranked penultimate in GDP, had 49.8% of consumption-based emissions transferring from other cities in the Basin.

Fig. 4 shows the major emission transfers among 47 cities in the region, which were more than 3 Mt. The background color of each city denotes the net value of emissions. Major transfers occurred in west upstream and the Pearl River Delta. Bijie and Liupanshui were the main net export cities, transferring carbon emissions to their provincial capital city Guiyang, where the total amount was nearly 10 Mt. Meanwhile, the scale of the transfers between downstream cities were much larger. Cities in, or near, the Delta transferred carbon emissions to the Pearl River Delta cities, mainly to Shenzhen and Guangzhou. There were seven cities which transferred more than 3 Mt to Shenzhen, and two cities to Guangzhou. Among them, the transfer volume from Guangzhou to Shenzhen was as high as 10.5 Mt. Although the transfers from all the other cities in the Basin to the Pearl River Delta cities were large, accounting for 19.2% of nine Delta cities' consumption-based emissions, most of these transfers were from the cites nearby the Delta and within the same province. The carbon transfers from upstream cities to the Pearl River Delta cities were not notable. The transfers from Bijie and

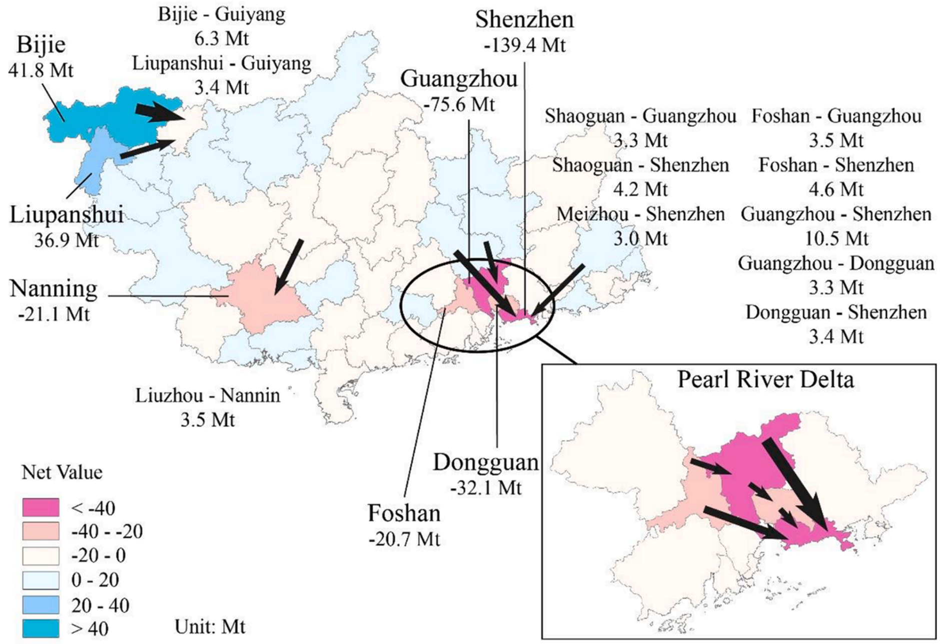

Fig. 4. Major carbon emission transfers among 47 cities in the five provinces of the Pearl River Basin.

Liupanshui to Shenzhen and Guangzhou were about 1 Mt, while all other transfers were less than 0.6 Mt, where most of which were less than 0.1 Mt.

Cities whose consumption-based emissions are greater than their production-based emissions (that is, the inflow emissions are greater than the outflow emissions) are categorized as consumer cities. Cities whose production-based emissions are greater than their consumption-based emissions are categorized as producer cities. These two names describe a city's position in the supply chain. Among all 47 cities, 28 cities were consumer cities and 19 were producer cities. The 13 cities with the largest GDP were all consumer cities. Shenzhen was a most typical consumer city, with consumption-based emissions of 153.1 Mt, which were 10.1 times its production-based emissions (13.7 Mt). The large consumption was characteristic of Shenzhen, where the consumption of a single city accounted for 19.6% of the entire Basin's consumption. Bijie and Liupanshui were the typical producer cities and their production-based emissions (58.8 Mt and 54.4 Mt) were respectively 3.5 times and 3.1 times of their consumption-based emissions (17.0 Mt and 17.5 Mt).

4. Discussion

Cities in the Basin should establish a coordinated emission reduction mechanism. Our research found that the level of consumption was one of the reasons for the inequality of carbon emissions per capita. All the 13 wealthiest cities in the Basin that generate the most GDP were consumer cities. That is, wealthier cities have higher consumption-based emissions and lower production-based emissions; while, poorer cities are just the opposite. It would be unfair for poorer cities to bear heavier emission reduction obligations if the responsibilities are only allocated on the basis of the production-based emission inventory. Affluent cities should provide a "emission reduction fund" to poor cities for upgrading technology to reduce emissions or for increasing carbon sinks, which will reflect the responsibility of consumers. Our research further supports the establishment of a provincial coordinated emission reduction mechanism, because the carbon transfers between cities in the same province were more significant than the emissions imported from other provinces. In addition, China began to establish a nationwide carbon emission trading market for the power industry in 2021 and the market will contain more emission industries in the future. This market will guide capital into enterprises with high emission reduction potential (Weng and Xu 2018; Li and Lu 2015). The coordinated emission reduction mechanism will help enterprises in poor cities gain a competitive advantage and thus help poor cities achieve emission reductions and even improve the level of economic development.

The Chinese government has proposed the Guangdong-Hong Kong-Macao Great Bay Area Development Plan and the Pearl River Economic Belt Strategy. The hope is to utilize developed Pearl River Delta cities, Hong Kong and Macau as the driving force for economic development, and use Pearl River shipping as a linkage to strengthen infrastructure construction and to build a strong bond between the upstream and downstream cities (Fang et al., 2020). The volume of trade between cities in the Basin will increase massively, and carbon emissions transfer from upstream cities to the Pearl River Delta will consequently increase. Moreover, the upstream cities of the Pearl River Basin are vigorously exploiting hydropower, which will make the energy cleaner and reduce their emission intensity. The total carbon emissions throughout the Basin will reduce if the energy or commodity consumption of the Pearl River Delta cities shifts to upstream production. Accordingly, the transfers of carbon emissions between cities in the Pearl River Basin is an issue worthy of long-term attention and basin-scale collaborative emission reduction will be the focus of future research.

Basin cities should formulate differentiated emission reduction policies. Our research showed that cities were located in different positions in the supply chain, and the main emission sectors of each city were also different. It is inefficient for all cities to adopt similar emission reduction policies. Producer cities should pay more attention to adjusting its energy structure, improving technological levels and energy efficiency. However, these policies are not efficient for consumer cities, who should pay attention to guiding its residents to a green lifestyle, or adjusting the production place structure of the goods and services needed. Cities with similar production-based emissions and consumption-based emissions should take the two kinds of policies mentioned above into consideration at the same time. In addition, cities with expressly higher consumption-based emissions should be taken as the core and the starting point for the design of regional emission reduction policies. Our results showed that all the provincial capital cities were such cities in accordance with consumption-based emissions.

Upstream cities should formulate green urbanization development strategies. Our research showed that the fixed capital investment played a major role in consumption-based emissions because of the low urbanization rate of cities in the upstream area. China mentioned in the "14th Five-Year Plan" that the national urbanization rate will be expected to reach 65% by 2025. It can be predicted that the upstream cities, whose urbanization rates ranging from 36.4% to 47.5%, will still experience a long period of rapid urbanization. These cities should deploy green infrastructure in advance, reduce the emission intensity of building materials, transportation and other industries, to avoid a substantial increase of carbon emissions in the future. And also try to establish low-carbon communities and low-carbon industrial parks.

5. Conclusion

In this study, we employed an entropy-based framework to construct the 2012 Pearl River Basin city-level MRIO table and compiled the consumption-based emission inventory of these cities, filling the data gap and providing policy recommendations for regional emission reduction. We found that the consumption-based emissions per capita of cities were inequitable. The emissions of the city with the largest per capita emissions were more than 10 times of the city with the smallest per capita emissions. This inequality was caused by the consumption per capita, the local consumption structure, and the source structure of consumed goods or services. We found that cities with high emissions are geographically concentrated. The 9 prosperous cities in the downstream Pearl River Delta emitted about half of the emissions of the entire Basin. Besides, the consumption-based emissions of the upstream cities were obviously dominated by investment, with a contributing ratio of about 70%. We identified that construction, heavy industry, and the service sector as the three sectors with the most consumption-based emissions. Furthermore, carbon emission transfers mainly occurred in the upstream cities and the downstream cities of the Pearl River Delta respectively. The trans-regional transfers from upstream to downstream were not significant.

The consumption-based emission inventory provides a more detailed data basis for the city’s emission reduction policy formulation. We propose to establish a coordinated emission reduction mechanism at the provincial level, which will improve the fairness of emission reduction behavior and bring new opportunities for the development of impoverished areas. It is suggested to develop differentiated reduction policies for different types of cities in terms of their positions on the supply chain, which will improve the efficiency of emission reduction activities. It is recommended that the upstream cities should formulate green urbanization development strategies to avoid a surge in emissions in the near future. Our next work will be compiling the MRIO tables of the Basin cities for more years to study the dynamic changes of city-level consumption-based emissions in the Basin and to provide the coordinated emission reduction suggestions at the basin scale.

Credit author statement

Yukun Qian: Experiment, Analysis, Writing and Revising
Heran Zheng: Methodology, Data curation and Revising
Jing Meng: Supervision
Yuli Shan: Data curation
Ya Zhou: Revising
Dabo Guan: Supervision

Declaration of Competing Interest

The authors declare no competing interests.

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Appendix

Table 1. List of 42 sectors of the MRIO table

code	Sectors	Category
1	Farming, Forestry, Animal Production and Fishery	Agriculture
2	Mining and Washing of Coal	Mining
3	Extraction of Crude Petroleum and Natural Gas	Mining
4	Mining of Metal Ores	Mining
5	Mining and Quarrying of Nonmetallic Mineral and Other Mineral	Mining
6	Manufacture of Food and Tobacco	Light Industry
7	Manufacture of Textiles	Light Industry
8	Manufacture of Textile Wearing Apparel, Footwear, Leather, Fur, Feather and Its Products	Light Industry
9	Processing of Timbers and Manufacture of Furniture	Light Industry
10	Papermaking, Printing and Manufacture of Articles for Culture, Education and Sports Activities	Light Industry
11	Manufacture of Refined Petroleum, Coke Products, Processing of Nuclear Fuel	Heavy Industry
12	Manufacture of Chemicals and Chemical Products	Heavy Industry
13	Manufacture of Nonmetallic Mineral Products	Heavy Industry
14	Manufacture and Processing of Metals	Heavy Industry
15	Manufacture of Fabricated Metal Products, Except Machinery and Equipment	Heavy Industry
16	Manufacture of General-Purpose Machinery	Heavy Industry
17	Manufacture of Special-Purpose Machinery	Heavy Industry
18	Manufacture of Transport Equipment	Heavy Industry
19	Manufacture of Electrical Machinery and Apparatus	Heavy Industry
20	Manufacture of Communication Equipment, Computer and Other Electronic Equipment	Heavy Industry
21	Manufacture of Measuring Instruments	Heavy Industry
22	Other Manufacture	Heavy Industry
23	Scrap and Waste	Service Industry
24	Repair of Fabricated Metal Products, Machinery and Equipment	Service Industry

(continued on next page)

(*continued*)

code	Sectors	Category
25	Production and Supply of Electricity and Steam	Production and Supply of Electricity and Steam
26	Production and Distribution of Gas	Production and Distribution of Gas and Water
27	Production and Distribution of water	Production and Distribution of Gas and Water
28	Construction	Construction
29	Wholesale and Retail Trade	Service Industry
30	Transport, Storage and Post	Service Industry
31	Accommodation, Food and Beverage Services	Service Industry
32	Information Transmission, Software and Information Technology Services	Service Industry
33	Finance	Service Industry
34	Real Estate	Service Industry
35	Renting and Leasing, Business Services	Service Industry
36	Scientific Research and Development, Technical Services	Service Industry
37	Management of Water Conservancy, Environment and Public Facilities	Service Industry
38	Services to Households, Repair and Other Services	Service Industry
39	Education	Service Industry
40	Health Care and Social Work Activities	Service Industry
41	Culture, Sports and Entertainment	Service Industry
42	Public Management, Social Security and Social Organization	Service Industry

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