# Carbon emissions of cities from a consumption-based perspective

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**Abstract:** Carbon emission inventories are the foundations of climate change mitigation and adaptation in cities. In this study, we estimated production-based $CO_2$ emissions from fossil fuel combustion and industrial processes in eleven cities in Hebei Province of China in 2012 and used input-output theory to measure their consumption-based $CO_2$ emissions. By comprehensively comparing production- and consumption-based emissions, we found that six developed cities were consumption based with import-depended trade patterns, while the five other cities were production based, mostly medium in size, with the potential to transform into consumption-based cities with socioeconomic development. Emissions embodied in imports accounted for more than half of the consumption-based emissions in most cities, which shows the significance of interregional cooperation in tackling climate change. International cooperation is also important at the city level, as international imports also impacts consumption-based emissions. From the perspective of final use, emissions caused by fixed capital formation predominated in most cities and were determined by their economic development models.

**Keywords:** Consumption-based accounting, production-based accounting, embodied $CO_2$ emissions, city, input-output model

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## 1. Introduction

Since the sharp growth of the global population and the continuous acceleration of the industrialization process in developing countries, the demand for fossil energy in human activities has increased in recent years [1, 2]. Global climate change caused by greenhouse gas emissions represented by $CO_2$ has become a common and serious problem faced by nations and regions around the world and is threatening human beings and the environment. Therefore, emission-reducing and energy-conserving strategies have become a worldwide consensus to respond to and mitigate global climate change. One of the most important steps is the accurate calculation of carbon emissions in various regions to clarify drivers and to allocate emission reduction responsibility to countries and economies [3]. The scientific and rational carbon emission accounting approach is a suitable basis for the determination and implementation of carbon emission reduction targets and policy formulations. At present, carbon emission accounting is still an international research hotspot, where the significant problem is how to distribute responsibilities among carbon producers and consumers.

There are two main approaches to measure carbon emissions: production-based accounting (PBA) and consumption-based accounting (CBA) [4, 5]. Currently, the most widely used carbon emission accounting approach is PBA, which calculates the carbon emissions from domestic production, including exports, in the producing process as the responsibility of the producer [6, 7]. PBA can constrain the carbon-emitting behaviour of producers and can promote producers to improve the energy efficiency of unit products. PBA can assist producers to address negative externalities. As PBA is widely applied in protocols pertaining to global climate change, many cities calculate carbon emissions from a production perspective and compile urban greenhouse gas emission inventories to be consistent with national-level accounting, which is conducive to horizontal comparison among cities. However, despite its obvious advantages, PBA does not consider the ultimate destinations and final consumers for goods and services [8]. When promoting the development of the global economy through trade redistributions [9, 10], producers and consumers of commodities will also be geographically separated due to trades, resulting in interregional emission transfer; thus, part of the emission-reducing responsibilities within borders are passed on to other areas [11-13]. By excluding indirect emissions, PBA cannot depict the overall picture of urban greenhouse gas emissions [14]. If direct carbon emissions are fully borne by exporting countries, it will be clearly unfair, and $CO_2$ emissions will not be effectively reduced [15]. Similarly, under PBA, cities with low production but high consumption in China tend to be considered low-carbon [16]. The failure to include indirect emissions will lead essentially to unfair assignments of emission reduction tasks, will further affect global emission reduction efficiency, and may even adversely affect active participation in reducing emissions. Consequently, the shift of carbon emission accounting from PBA to CBA has gradually received attention from the academy [17-19].

Compared to PBA, CBA calculates the total carbon emissions of final products including imports, where the responsibility for carbon emissions is borne by consumers [20]. This approach attributes direct emission responsibilities to the final consuming sectors; consequently, it characterizes the impact of human consumption choices on climate change. First, its main advantage is to reduce carbon leakages among cities and encourage spill-overs of emission-reducing technologies [21]. In addition, the index of emission per capita according to CBA more realistically reflects $CO_2$ emission responsibilities of urban residents. At the policy level, this approach encourages public consumption which is resource-saving by receiving goods and services through the public sector, curbs private consumption with high emission intensity, promotes the purchase of products and services from cleaner production areas, and greens the entire supply chain of urban products [22]. At present, research on global carbon emissions and related issues based on CBA focuses on the $CO_2$ emission-reducing responsibilities of regions under the CBA system [23-25]. As global carbon emissions calculated by CBA are also increasing annually [26], it is particularly important to analyse global carbon emissions and their influential factors according to CBA. In general, the above studies of CBA based on the input-output analysis are relatively advantageous [21, 27], as they not only contribute to a deep understanding of the influence on regional carbon emissions accounting by interregional trades but also provide an important theoretical basis to fairly and reasonably allocating responsibilities and analysing the role of carbon transfer in global climate governance.

A large number of studies have explored the feasibility of using CBA to calculate carbon emissions and determine national emission responsibilities, to analyse consumption-based carbon emissions at both global and national levels. At the global level, research has studied emission characteristics triggered by multinational trades [28, 29]. At the national level, consumption-based carbon emissions have been assessed in many countries, such as Australia [30], China [31, 32], Italy [33], Japan [34], Spain [35], Turkey [36], and the UK [37]. However, with the rapid growth of China's urban population, rapid industrialization and urbanization have led to an increasing demand for energy, causing a significant amount of greenhouse gas emissions [38]. Thus, cities are crucial to implementing carbon emission mitigation policies in China. Studies on emission inventories at the city level are limited, and mostly focus on PBA [39, 40]. Only a few studies have investigated consumption-based cities [41-43]. For example, Hasewaga [44] found that emissions calculated based on PBA were significantly different from those based on CBA in Japan. Feng [45] studied four megacities in China using CBA and found that urban consumption resulted in high emissions in surrounding areas through interregional trades. Given the reflections above, this study compares CBA and PBA among cities from the perspective of carbon emission accounting to fill a research gap on the position of CBA at the city level. The focus is specifically on cities in China.

Although more research has shifted the focus to the city level, the paper specifically presents a coherent sample from the same province, offering relatively useful data compared to irregularly distributed city data in China. This province is key for China’s economic transformation to address climate change. From the current urbanization and industrialization in China, energy conservation and emission reductions have achieved remarkable achievements with declining urban energy consumption and industrial emissions [46]. As a major industrialized province in China, Hebei is under considerable pressure with respect to emission reductions; the large-scale development and transformation of energy resources in this province have promoted rapid economic growth but have also led to a continuous increase in carbon emissions. The increasing carbon emissions in Hebei Province, as a typical energy-consuming province in China, are closely related to rapid economic development and changing energy consumption structures. More specifically, the demand for primary energy is still high in Hebei Province, which is now in the stage of rapid development of industrialization and urbanization. Hence, it is essential to improve the structure of consumption and upgrade industrial technology to control the carbon emissions of this province. Simultaneously, the development level and industrial degree of different cities in Hebei Province vary widely, resulting in different levels of energy consumption and carbon emissions among cities.

This paper closes the research gaps from the following aspects. First, with the rapid development of the urbanization, cities are crucial to mitigate carbon emissions [47]. However, studies on emission inventories based on CBA at the city level are limited [48], especially in China [49]. This study analyses carbon emissions of cities from a consumption-based perspective. In addition, given the data availability, most studies focus on selected cities which lose the whole picture of a province [50], while this paper uses data from each city in Hebei Province. In summary, addressing an emerging agenda of previous research, this study aims to analyse carbon emissions in urban China. The focus is on cities in Hebei province, and an analysis of CBA compared to PBA, thereby providing a scientific basis for strengthening carbon emission management and formulating emission reduction policies.

## 2 Method and data

### *2.1 Consumption-based carbon emission accounting*

As the input-output (IO) model quantifies the network and relationship among industries in the national economy by collecting currency transactions of sectors, it has been widely applied with expansions across various aspects [51, 52], including $CO_2$ emissions [53-55], energy consumption [56-58], resource use [59-61] and other environmental studies [62-64]. Consumption-based carbon emissions can be accounted by the IO model. Specifically, carbon emissions directly or indirectly embodied in the final goods and services consumed are estimated by CBA. In terms of environmental accounting, exogenous transactions expressed as emissions or energy are exchanged among each national sector and represent the direct and indirect consumption of products from different industries embodied in the final demand. In this study, PBA is first measured from energy consumption and industrial processes in Chinese cities [43, 65]. CBA is based on the following relationship: "CBA = consumption-based emissions from local production + emissions embodied in imports (domestic & international) = production-based emissions - emissions embodied in exports (domestic & international) + emissions embodied in imports (international & domestic)", which shows that the import and export commodities play an important role in quantifying real emissions [66].

The basic framework of the input-output theory was developed by Wassily Leontief in the quantitative input and output analysis of the economic system in the late 1930s [67]. To estimate

CBA at the city level, the standard environmentally extended input-output method is applied in this study, using the fundamental equation known as the Leontief equation:

$$X = \left(I\text{-}A\right)^{-1} F \tag{1}$$

where $X$ denotes the total output vector of $x_i$ representing the output of economic sector $I$; $F$ denotes the final demand vector of $f_i$ including the domestic use and international export of sector $i$; $I$ is the identity matrix; $A$ is the technical coefficient matrix showing the inter-sectoral flows; and $(I\text{-}A)^{-1}$ is the Leontief inverse matrix.

To evaluate CBA, the calculation of $CO_2$ emissions embodied in the final demand requires the emission intensity vector $E$, which is composed of the coefficient that indicates the $CO_2$ emissions per unit of industrial output $e_i$ in economic sector $i$; thus, the $CO_2$ emissions in CBA can be estimated as follows [68, 69]:

$$C = E\left(I\text{-}A\right)^{-1} \hat{F} \tag{2}$$

where $C$ denotes the vector of total $CO_2$ emissions embodied in the end-use products, $E=[e_1 e_2 \ldots e_n]$ represents the row vector of emission intensity associated with each industry sector, and $\hat{F} = diag(F)$ means that $\hat{F}$ is the diagonal vector of $F$ [6].

Although $C$ is calculated based on the total emissions embodied in the final demand, it cannot separate local production and outside imports. Because detailed import-related data are not available, the information obtained at the national level is used to estimate the $CO_2$ emissions embodied in imports, which are briefly described as:

$$C^{im} = E^{im}\left(I\text{-}A^{im}\right)^{-1} \hat{F}^{im} \tag{3}$$

where $C^{im}$ denotes the vector of total $CO_2$ emissions embodied in the import including both domestic and international imports, $E^{im}$ represents the row vector of the national emission intensity, $A^{im}$ is the technical coefficient matrix adjusted by the import share, $F^{im}$ is the import, and $\hat{F}^{im} = diag(F^{im})$ indicates that $\hat{F}^{im}$ is the diagonal vector of $F^{im}$. Similarly, the information at the national level is used to estimate the $CO_2$ emissions embodied in domestic and international exports. Given the availability of data, emissions caused by residential energy consumption are not considered in this study.

### *2.2 Data sources*

In this study, in which the CBA is calculated for eleven cities in Hebei Province, China, three sets of data are mainly used, i.e., input-output tables, populations and $CO_2$ emissions of cities. The input-output tables at the city level are obtained from regional statistics bureaus. Population data are derived from the database of the National Bureau of Statistics of China [70]. Data on carbon emissions are not officially released in China, and the data quality of cities is relatively poor except for megacities. Consequently, a method to construct a production-based $CO_2$ emissions inventory for cities in China is developed in this study according to the definition provided by the IPCC territorial emission accounting approach [71, 72]. There are 9 primary industry products, 20 energy types and 47 socioeconomic sectors in each inventory. The concordance of 45 sectors (excluding the urban and rural) in emission inventory data and 42 sectors in the IO table is shown in Table S1 in supplementary information.

All the imports including domestic and international imports are from IO tables. In the IO table, there is a sum relation that for a specific sector, its "intermediate output + final demand - net imports = total output". Therefore, the domestic and international import data are included in the IO table. Details for the IO layout could be found in WIOD [73]. The IO tables at the city level are from local bureau of statistics [74-77]. By aggregating the $CO_2$ emissions from different fossil fuels and sectors, we obtained the total $CO_2$ emissions. All data are sourced from China Emission Accounts and Datasets, which is a free China energy data sharing platform [78].

In IO analysis, there are several assumptions: (1) it assumes that same quantity of inputs is needed per unit of output, regardless of the level of production; (2) it assumes fix input structure which means any change in output would not change the input structure; (3) the model assumes that an industry uses the same technology to produce each of its products; (4) it assumes static model which means no price would change. The $CO_2$ emission intensity in this paper uses survey based on a study [79] instead of IPCC default data [80], which can increase the accuracy of results. Because of assumptions in IO analysis, all products in one sector are treated as homogeneity, which means different products in one sector are treated same. This can lead to the aggregation error, where different products in one sector can be different in terms of emissions. Although it may have some uncertainty in the results because this is the endogenous assumption, the production-based emissions are distributed into each production process in IO technique. Thus, the total emission can be constrained and results can be accepted.

## 3. Results and Discussion

### *3.1 Consumption-based emissions for eleven cities in Hebei, China*

The compositions and causes of consumption-based emissions in eleven cities in Hebei, China, were analysed. These varied across cities but showed certain regional and structural characteristics.

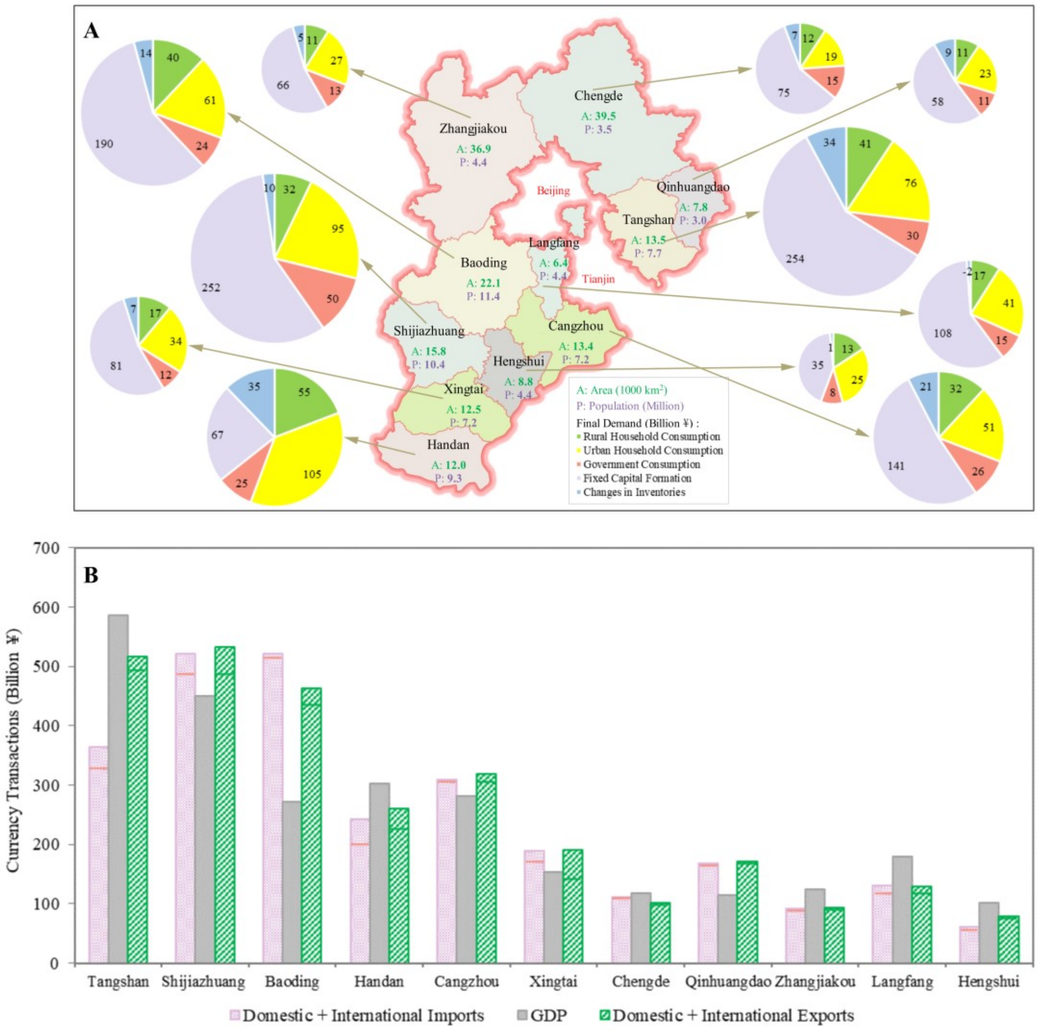

**Fig. 1.** (A) Socioeconomic information for eleven cities in Hebei in 2012. *A* represents the area of each city (in 1000 km$^2$). *P* denotes the population of each city (in millions). Total final demands are shown in the pie charts (in billion ¥), with the five colours representing rural household consumption, urban household consumption, government consumption, fixed capital formation and changes in inventories. (B) GDP and trade in monetary units for eleven cities in Hebei in 2012. Total imports (left), GDP

(middle) and exports (right) are shown in the bar charts (in billion ¥), with both domestic (bottom) and international (top) transactions.

Although the population density in central and southern Hebei is relatively high, with two cities in the north sparsely populated, the final demand structure with the largest contribution by fixed capital formation was similar for each city in 2012 except the southernmost, Handan (**Fig. 1A**). The population density is related to the geographic location. Cities with the lowest population density in Hebei are northern cities, Chengde (89 persons/km$^2$) and Zhangjiakou (119 persons/km$^2$). This is attributed to their areas being ranked first and second and is also likely because Chengde and Zhangjiakou are bordered by Liaoning Province to the northeast and Inner Mongolia Province to the northwest, respectively, where relatively poor economic performance and massive migration in recent years affects social development and living conditions. In contrast, Baoding and Langfang benefit from geographical advantages. The former has the largest population (11 million) as a result of connecting the capital Beijing to the provincial capital Shijiazhuang, and the latter, located between two municipalities (Beijing and Tianjin) has the second largest population density (691 persons/km$^2$). Additionally, there is a clear relationship between the demand structure and the population density. The savings rate in China has been high for a long time, which makes investment rather than consumption a major driver of domestic demand [81]. Therefore, most cities in Hebei are characterized by the capital formation accounting for the largest proportion at an average of 55% of the final demand, followed by urban consumption and then government and rural consumptions. However, the largest percentage of the final demand in Handan is urban household consumption (105 billion ¥, 36%) rather than fixed capital formation (67 billion ¥, 23%). Handan ranked first by population density (774 persons/km$^2$) in Hebei.

GDP, domestic plus international imports and exports for eleven cities in Hebei in 2012 were analysed by classifying them into different types (**Fig. 1B**). The top two cities with the highest GDP were the industrial centre Tangshan (586 billion ¥) and the provincial capital Shijiazhuang (450 billion ¥), while the city with the lowest GDP was Hengshui (101 billion ¥). However, the GDP in the above three cities approximately doubled compared with that in 2007 [43]. Because the population remained almost unchanged, the GDP per capita in Tangshan (76,000 ¥/person) was also the highest, followed by the relatively developed cities Shijiazhuang (43,000 ¥/person) and Langfang (40,000 ¥/person). By comparing their final demand with their imports, cities were classified into an external-depended type with the former lower than the latter represented by Baoding and Qinhuangdao and an internal-oriented type with greater final demand represented by Tangshan and Langfang. In terms of imports and exports, currency transactions in imports and exports were similar in most cities with a few exceptions. For example, Baoding is a typical import-depended city (521 billion ¥), while Tangshan is a typical export-oriented city (517 billion ¥). Specifically, areas with better industrial systems had international imports occupying more than 5%, including Tangshan (10%), Shijiazhuang (7%), Handan (18%), Xingtai (9%) and Langfang (11%). Simultaneously, domestic imports in less developed regions far exceeded international imports, which accounted for no more than 2%, including Baoding (2%), Cangzhou (1%), Chengde (0.1%), Qinhuangdao (1%), Zhangjiakou (0.5%) and Hengshui (2%).

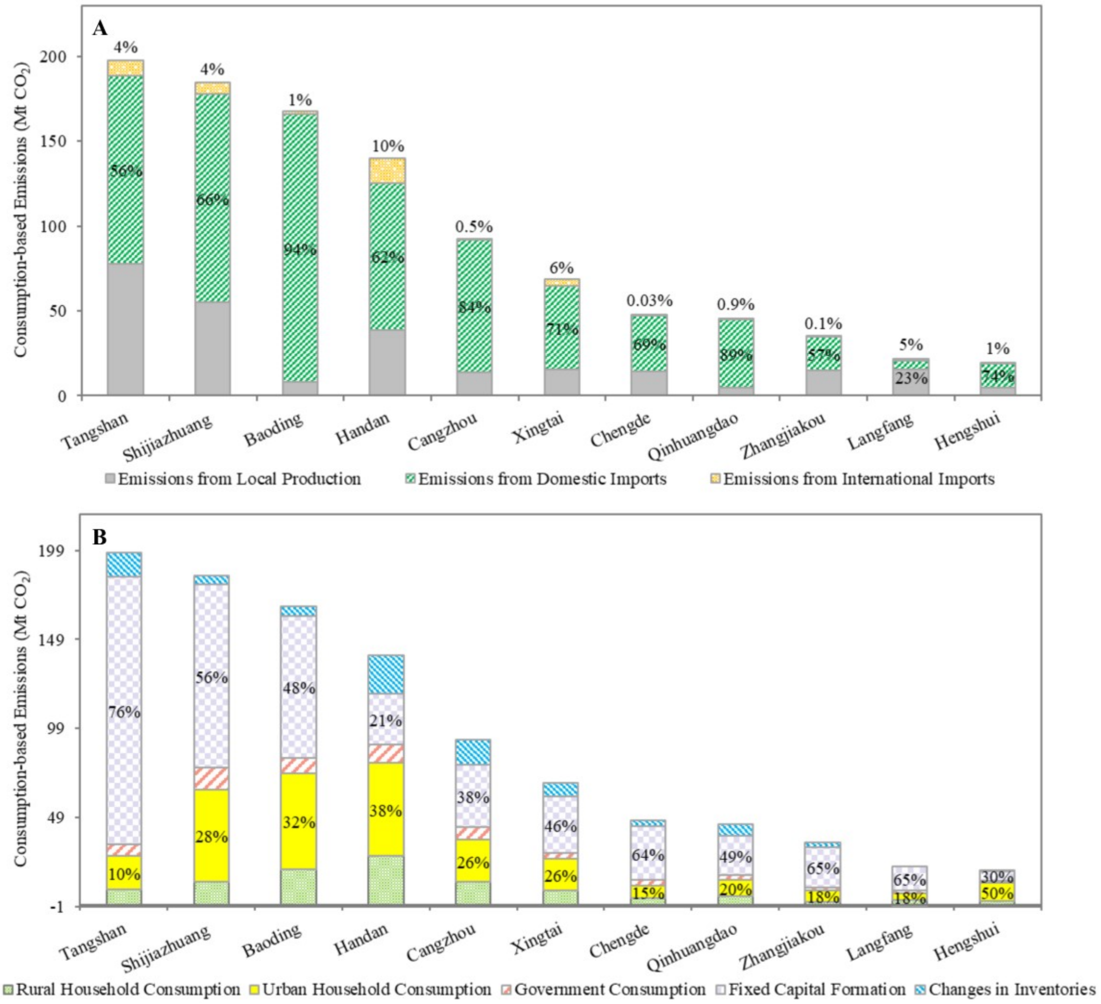

**Fig. 2.** (A) Consumption-based emissions from local production, domestic imports and international imports in eleven cities of Hebei in 2012. The percentages of emissions embodied in domestic and

international imports are shown inside and above the bars respectively. (B) Consumption-based emissions for five final demand categories for eleven cities in Hebei in 2012. The percentages of emissions embodied in urban household consumption and fixed capital formation are shown at the bottom and top of the bars, respectively.

The emissions caused by domestic and international imports in each city in 2012 accounted for a large percentage of total consumption-based emissions, including emissions embodied in total imports and emissions attributed to the consumption of local products (**Fig. 2A**). From the perspective of an absolute amount, consumption-based emissions varied widely among cities in the same province and were affected by the final consumption and imports mentioned above. Compared with the smallest emitter Hengshui (19 Mt $CO_2$), Tangshan ranked first (198 Mt $CO_2$), with approximately 10 times the consumption-based emissions of Hengshui. Furthermore, products imported from elsewhere in China and foreign countries might result in higher emissions compared with products produced and consumed within city boundaries. For instance, imports into Qinhuangdao were 18% higher than those into Langfang, resulting in two-fold higher emissions in Qinhuangdao (45 Mt $CO_2$) compared with Langfang (22 Mt $CO_2$), and the total consumption in Qinhuangdao (280 billion ¥) was lower than that in Langfang (310 billion ¥). From the perspective of relative proportion, import-embodied emissions in 2012 were far higher than self-produced emissions in most cities. In 10 cities of Hebei, only with the exception of Langfang, more than 50% of consumption-based emissions were attributed to imports from external regions at home and abroad, which indicates that consumption relied heavily on foreign products as opposed to local products. The above results are consistent with previous studies on cities that showed approximately 70% $CO_2$ emissions in China were attributed to imports [43], and 40%-80% in Japan [44]. According to the analysis of socioeconomic information, Baoding (95%) and Qinhuangdao (90%), the two top-ranked cities in terms of proportion of imported emissions, corresponded with their external-depended types, as imported consumption exceeded final demand. Similarly, Langfang (28%) and Tangshan (60%) accounted for the minimum percentages of imported emissions because they are typical internal-oriented type cities. Imports, as a driver of consumption-based emissions, can be further divided into domestic and international imports, which would lead to different import-emitting structures. Corresponding with the analysis above, international-imported emissions accounted for at least 4% in cities in which international imports dominated, including Tangshan (4%), Shijiazhuang (4%), Handan (10%), Xingtai (6%) and Langfang (5%), while fewer imports from abroad resulted in emissions from international imports that did not exceed 1%, i.e., Baoding (1%), Cangzhou (0.5%), Chengde (0.03%), Qinhuangdao (0.9%), Zhangjiakou (0.1%) and Hengshui (1%). Hence, with a considerable contribution from emissions embodied in international imports, it is important to strengthen international cooperation at the city level.

Similarly, the emissions caused by fixed capital formation in each city in 2012 accounted for a large percentage of total consumption-based emissions in the five final demand categories, including rural household consumption, urban household consumption, government consumption, fixed capital formation and changes in inventories (**Fig. 2B**). The maximum proportion of emissions was driven by capital formation, followed by urban household consumption, in most cities in Hebei with the top three being Tangshan (76%), Zhangjiakou (65%) and Langfang (65%), which reveals that the demand relied heavily on investment as opposed to consumption. The above results are consistent with other research on $CO_2$ emissions in China [43, 82-84], where development models including rapid but insufficient economic growth associated with domestic demand, as well as extensive urbanization and government-led stimulus policies are the reasons for the largest contribution from capital investment. However, Handan and Hengshui were exceptions, as urban household consumption contributed more than capital formation consumption. Specifically, urban households emitted more (38%) than capital formation (21%) in Handan based on its final demand structure mentioned above, while proportions ranked differently for emissions and final demand in Hengshui mainly because of its industrial consumption structure. In Hengshui, the emissions caused by urban consumption (50%) accounted for more than those from capital formation (30%); however, the urban consumption percentage (30%) of the final demand was lower than that of capital formation (43%). An underlying explanation is that the industrial sectors with high emissions intensity consumed more, but invested less. To provide a clear explanation, Hengshui is compared with Handan, which shows a similar structure in terms of emission proportions. Hengshui is famous for education, with highly reputed schools, and the urban household consumption exceeded the normal level in education-related industries, including several high-emission intensity sectors (“papermaking, printing and manufacture of articles for culture, education and sports activities”, “manufacture of communication equipment, computer and other electronic equipment", "production and supply of electric power and heat power", and "education"), which led to more emissions for the same amount of total urban consumption. However, capital formation did not occur in sectors with high emission intensity ("processing of timbers and manufacture of furniture", "manufacture of nonmetallic mineral products", "manufacture of metal products", "scrap and waste", etc.), resulting in a significant reduction in emissions from investment in these sectors.

*3.2 Consumption-based and production-based emissions of eleven cities*

Following the relationship "local-produced emissions = CBA - imported emissions (domestic & international) = PBA - exported emissions (domestic & international)", emissions from consumption of imports and production of exports for eleven cities in Hebei, China, were compared.

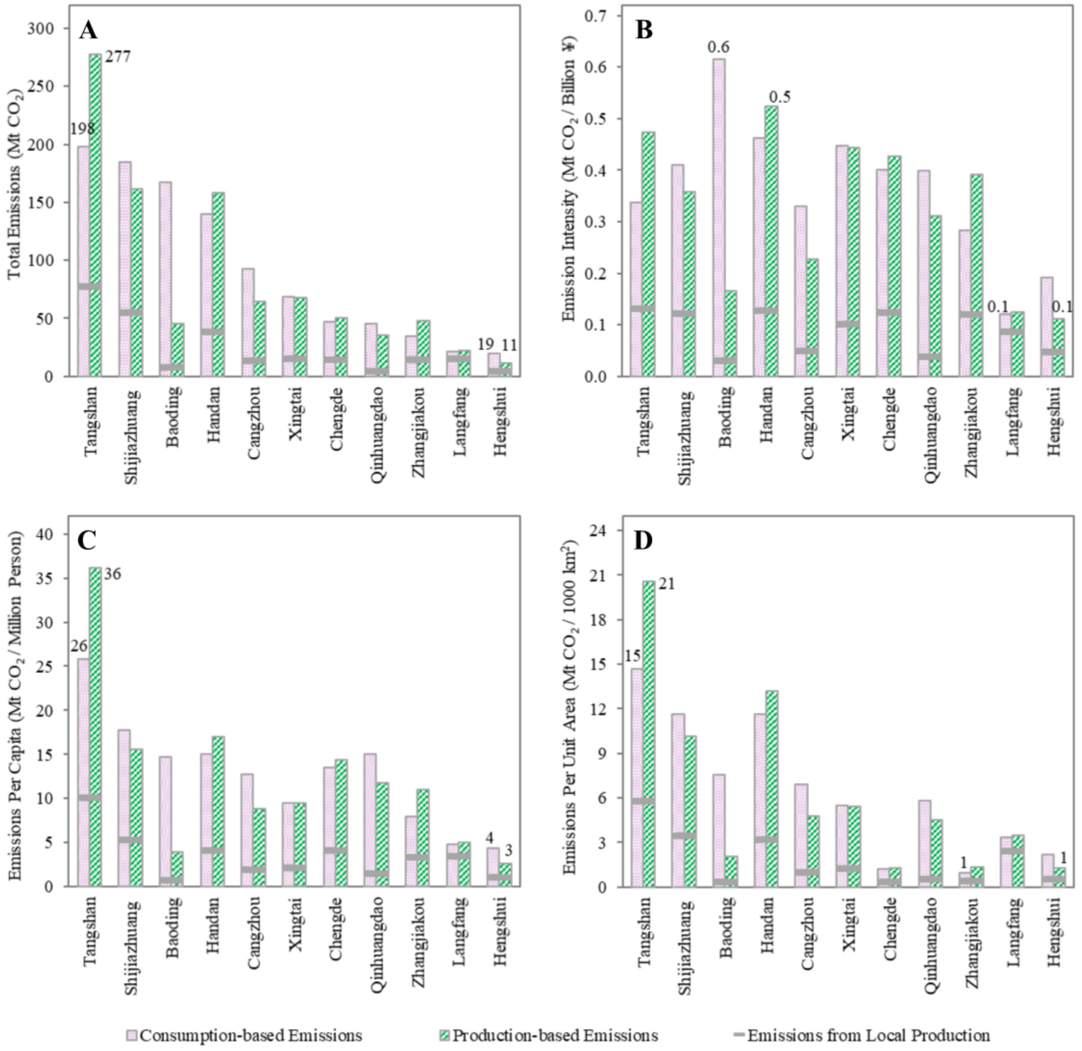

**Fig. 3.** (A) Total consumption-based emissions, production-based emissions and emissions from local

production at the city level in Hebei in 2012. The highest and lowest emissions associated with consumption and production are shown above the respective bars. (B) Consumption-based, production-based and locally produced emission intensity for eleven cities in Hebei in 2012. (C) Consumption-based, production-based and locally produced emissions per capita in eleven cities of Hebei in 2012. (D) Consumption-based, production-based and locally produced emissions per unit area for eleven cities in Hebei in 2012.

Cities in Hebei were categorized into consumption-based cities and production-based cities with large differences in the source of emissions (**Fig. 3A**), which were mainly caused by the trade pattern and emission intensity [85, 86]. Shijiazhuang, Baoding, Cangzhou, Xingtai, Qinhuangdao and Hengshui were classified as consumption-based cities and had consumption-based emissions higher than production-based emissions. According to the above two reasons, Baoding, as a typical import-depended city analysed in *3.1*, was classified as a consumption-based type, mainly due to its trade pattern, with emissions from consumption (168 Mt $CO_2$) almost four times higher than the amount of production-based emissions (45 Mt $CO_2$). In addition, Qinhuangdao, as an example of a city with similar imports and exports, was classified as a consumption-based city with higher emissions from consumption (45 Mt $CO_2$) than from production (35 Mt $CO_2$) because of its high emission intensity of imports (0.4 Mt $CO_2$/billion ¥). Production-based cities with higher emissions from exports than from imports included Tangshan, Handan, Chengde, Zhangjiakou and Langfang. The typical export-oriented trade pattern led to production-based emissions (277 Mt $CO_2$) being larger than consumption-based emissions (198 Mt $CO_2$) in Tangshan, and Zhangjiakou, with similar imports and exports, emitted more from production (48 Mt $CO_2$) than from consumption (35 Mt $CO_2$), caused by the high emission intensity of exports (0.4 Mt $CO_2$/billion ¥). Furthermore, the findings reveal a large gap between CBA and PBA, which demonstrates that PBA benefited consumption-based cities in allocating responsibilities. Thus, production-based cities have proposed widespread application of CBA for climate change mitigation. Notably, the five production-based cities in Hebei mentioned in the results are consistent with the conclusion that most medium-sized cities are production-based cities [43]. In addition, the result of using cities that exhibit both similarities and differences within one province as good examples indicating that most developed cities in China are consumption-based cities, according to [43], was expanded to both developed and less developed regions. In fact, the former was proved to be caused by the predominant import trade pattern, while the latter mostly imported consumption-based products with a high emission intensity, which might be due to unimproved technology or primary industries. Shijiazhuang transformed from a production-based city in 2007 to a consumption-based city in 2012 due to its rapid economic development as the provincial capital of Hebei, which provides evidence of the inference made in [43].

The difference in total production-based emissions between the highest emitter Tangshan (277 Mt $CO_2$) and the lowest emitter Hengshui (11 Mt $CO_2$) was approximately 25-fold, which was higher than that of consumption-based emissions (10 times higher). However, only Hengshui (0.1 Mt $CO_2$/billion ¥) retained at the same ranking for production-based emission intensity, and Langfang (0.1 Mt $CO_2$/billion ¥) replaced Hengshui with the lowest consumption-based emission intensity. Baoding (0.6 Mt $CO_2$/billion ¥) and Handan (0.5 Mt $CO_2$/billion ¥) ranked first in consumption- and production-based emission intensity, respectively (**Fig. 3B**). Adjusted by per unit GDP, the differences among cities in consumption-based, production-based and local produced emissions decreased. The emission intensity of local production was divided into two groups by approximately 0.1 (Mt $CO_2$/billion ¥) or less, which indicated that the supply-demand structure was similar, and the socioeconomic development was balanced in each city of Hebei. In addition to the efficiency adjustment of GDP, the remaining two emissions intensities of imports and exports were also affected by the sectoral consumption structure and industrial technology level. In terms of emissions per capita, with an even population distribution in Hebei, the rankings of three cities in the north, i.e., Chengde, Qinhuangdao and Zhangjiakou, with relatively sparse populations increased slightly compared with total emissions (**Fig. 3C**). Similarly, with regard to emissions per unit area, the large area of Zhangjiakou resulted in the smallest consumption-based emissions per unit area, with the rankings of Tangshan and Hengshui retained (**Fig. 3D**). Hence, different accounting approaches with various criteria should be integrated into policies pertaining to emission reduction.

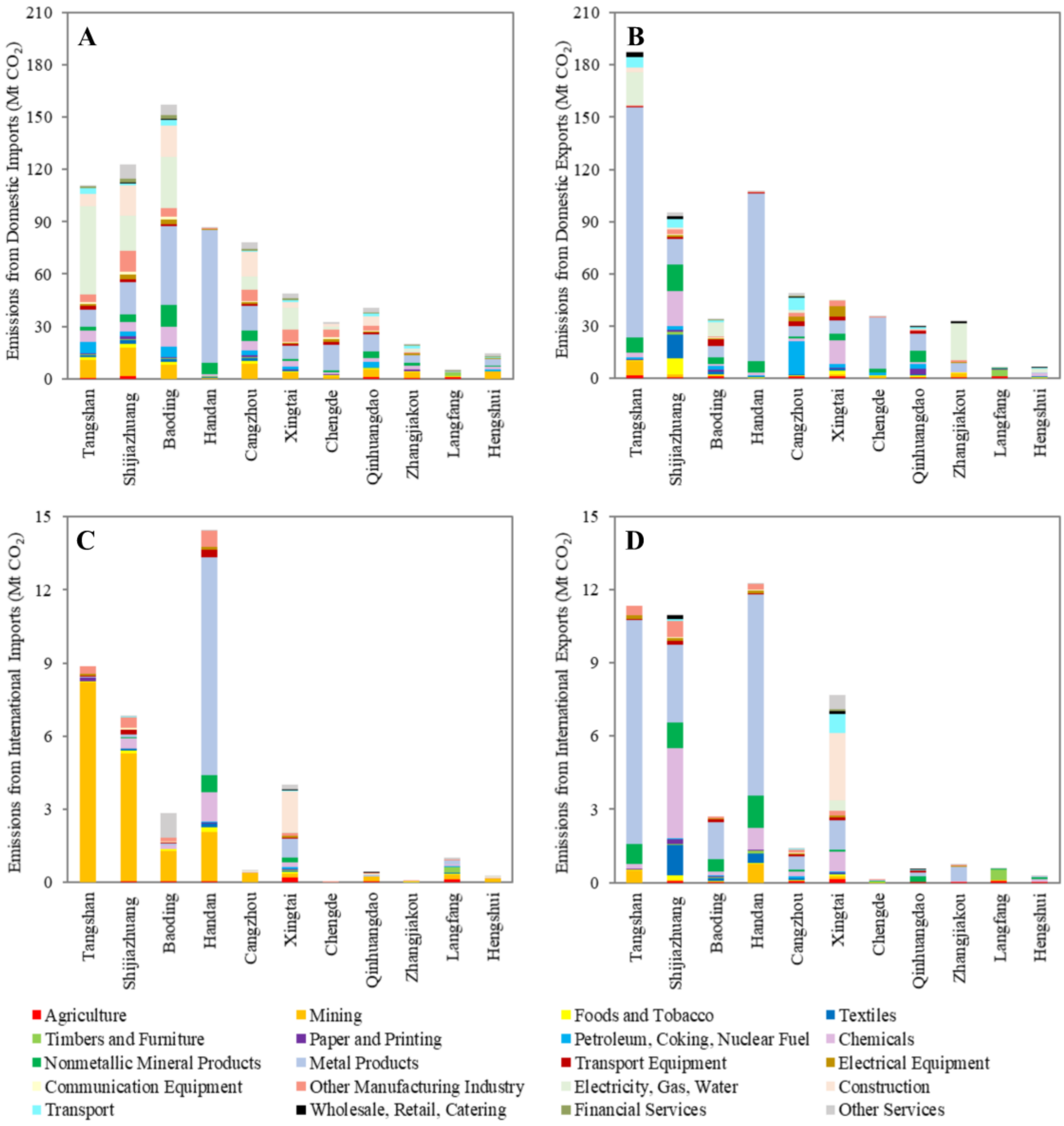

**Fig. 4.** (A) $CO_2$ emissions embodied in domestic imports by sector for eleven cities in Hebei in 2012. (B) $CO_2$ emissions embodied in domestic exports by sector for eleven cities in Hebei in 2012. (C) $CO_2$ emissions embodied in international imports by sector for eleven cities in Hebei in 2012. (D) $CO_2$ emissions embodied in international exports by sector for eleven cities in Hebei in 2012.

Emissions embodied in imports and exports were determined by the volume of imports and exports and the consumption structure; higher emissions were caused by increasing consumption in sectors with a high emission intensity. The domestic imports of Baoding (512 billion ¥) resulted in the highest emissions from domestic imports (157 Mt $CO_2$), while emissions embodied in domestic imports of Chengde (33 Mt $CO_2$) were almost 7 times the amount of Langfang (5 Mt $CO_2$), and its domestic imports (112 billion ¥) were slightly lower than those of Langfang (116 billion ¥) (**Fig. 4A**). Emissions embodied in domestic exports of the largest emitter, Tangshan (188

Mt $CO_2$), were significantly higher than those of Shijiazhuang (95 Mt $CO_2$); domestic exports ranked first in the former (494 billion ¥) followed closely by the latter (486 billion ¥). This might be caused by the historic heavy industrial system in Tangshan compared with Shijiazhuang with its upgraded industrial structure in the period 2007-2012 (**Fig. 4B**). Handan was ranked first in emissions from international imports (14 Mt $CO_2$) due to the highest level of these imports (43 billion ¥). Emissions embodied in the international imports of Tangshan (9 Mt $CO_2$) were slightly higher than those of Shijiazhuang (7 Mt $CO_2$), contrary to domestic imports, and this corresponded with the international imports of the former (36 billion ¥) and the latter (35 billion ¥) due to the similar structure of sectoral consumption (**Fig. 4C**). In contrast to the findings above, sectors in Xingtai produced lower emissions associated with international exports, with the system focusing on tertiary industry, although this city had the highest level of international exports. Handan, Tangshan and Shijiazhuang were the top three emitters in terms of international exports due to their massive emissions from sectors represented by metal products (**Fig. 4D**).

In general, the metal product sector contributed the most to emissions, which is consistent with previous research [43]. Therefore, Hebei still needs to improve technology, upgrade industry, and transform the structure. A vertically comparison of domestic and international emissions indicated that total domestic imports and exports were much higher than the total international values. Moreover, domestic emissions in each city decreased successively, while international emissions were concentrated in the maximum and minimum extremes with a sizeable gap in the centre. A horizontally comparison of imported and exported emissions indicated that the relative size of total imports and exports corresponded to the type of city, i.e., consumption based or production based. As most cities in Hebei have a secondary industrial system, the proportion of emissions from the tertiary industry related to imports was higher than that related to exports. More specifically, emissions from domestic and international imports varied widely among sectors; emissions from domestic imports were mostly embodied in electricity, gas, water and metal sectors, while emissions from international imports were mainly embodied in mining. This is because goods and services from other domestic regions generally indicate China's industrial characteristics and technical level according to the comparative advantage. However, products from other countries abroad will show large differences compared to domestic products. Although there were different structures of emissions at home and abroad in the import sectors, emissions from domestic and international exports were similar in structure, i.e., both concentrate in metal products. This is a result of exporting products from advantageous industries based on the factor endowment.

## 4. Conclusions

A key suggestion from the analysis is that different emission accounting approaches have a strong influence on issues of allocating responsibilities to mitigate climate change. In the analysis, $CO_2$ emissions of eleven cities in Hebei, China, were measured by CBA compared with PBA to supplement mitigation policies. Based on different consumption structures, including final demand plus domestic and international imports, cities not only emit carbon within boundaries but also absorb carbon through interregional trade. The final demand is relatively high in internal-oriented cities with self-produced consumption, which, in turn, is associated with population density affected by geographical location. For instance, urban consumption may exceed capital investment in final demand due to a large population density. In addition, the consumption structure will also influence external-dependent cities, which are divided into export-oriented and import-dependent types, including domestic and international imports by sectors with $CO_2$ from different energy uses. According to a range of socioeconomic factors, different drivers cause different compositions of emissions across cities.

With respect to consumption-based emissions, imported emissions from domestic and international goods and services in ten cities (excluding Langfang) in 2012 are much higher than self-produced emissions embodied in local products, accounting for typically more than 50% of consumption-based emissions attributed to imports from external regions at home and abroad. From the perspective of the imported proportions in emissions, consumption at the city level is mostly determined by goods and services from other regions and foreign countries rather than local products. Therefore, both national systems in China and global mechanisms among economies are generally established through policies aimed at strengthening cooperation between carbon-consuming and carbon-producing regions for climate change mitigation. In terms of consumption-based emissions caused by trade within national borders, in the Chinese case a national emissions trading scheme (ETS) has been established based on trial transactions among carbon trading system pilots. This scheme has coordinated production relations, balanced emission shares, strengthened synergistic effects, and mitigated aggregate changes in China. In addition, the interregional clean development mechanism (CDM) in China will promote cities or provinces with cleaner production to buy carbon emission permits by investing in less developed regions or areas for improved technologies and upgraded industries. Furthermore, the design and operation of mechanisms in developed economies, represented by the European Union Emissions Trading System (EU ETS), have been advanced by improvement with extensive practice, and those mechanisms play an important role in coordinating global actions of carbon emissions and climate change among countries. Excellent mechanisms should not only be used as references and examples of best practice, but should also establish active and widely distributed involvement. From the perspective of international cooperation, interregional organizations have been addressing climate change mitigation through multilateral frameworks at the city level. For instance, the Local Governments for Sustainability (ICLEI), representing more than 20% of the world's urban population, has connected more than 1500 cities in 86 countries through a global committee. The C40 Cities Climate Leadership Group (C40), with more than 80 megacities covering more than 600 million people and 25% of the global economy, is aimed at a sustainable and low-carbon network of cities.

The emissions caused by fixed capital formation in most cities in Hebei in 2012 account for the largest proportion, followed by urban consumption and then government and rural consumptions in terms of total consumption-based emissions, which shows that the demand is predominantly driven by investment rather than consumption in China due to a high savings rate. Taking Hebei as an example, compositions of emissions were determined by the structures of the both final demand and industrial consumption in China; cities emit less by consuming or investing in sectors with a low emission intensity. By encouraging demand and accelerating urbanization, the final demand structure in China will shift from capital investment and rural consumption to urban household consumption. Simultaneously, the consumption structure in China will likely transition from high-emission intensity sectors to low-carbon industries with technical and model improvements in economic development.

By comparing emissions from imports, exports and local production for eleven cities in Hebei, cities in China can be categorized as consumption- and production-based cities depending on the source of emissions. Because trade pattern and emission intensity are the main causes of the different types, six consumption-based cities, Shijiazhuang, Baoding, Cangzhou, Xingtai, Qinhuangdao and Hengshui, are deemed typical import-dependent cities or those with a high emission intensity from imports. This finding reveals that both developed and less developed cities in China might be consumption-based cities. However, production-based cities in China are mostly medium-sized. Examples from the Hebei case include Tangshan, Handan, Chengde, Zhangjiakou and Langfang. The above five cities are typical export-oriented types with high emission intensities from exports. Taking Shijiazhuang as an example, production-based cities would transform into consumption-based cities in the process of their socioeconomic development from medium-sized cities to metropoles. Notably, an increasing number of regions and economies have made efforts to promote the improvement of emission accounting approaches by comprehensively considering CBA and PBA with reference to various criteria based on GDP, capita or area to fairly allocate responsibilities.

In general, the activity of reducing emissions is closely related to industry upgrades and structural transformation in China because cities emit less by importing or exporting in sectors with low emission intensities. For instance, the metal product sector in Hebei contributed the most to emissions from imports and exports. Hence, technology improvement in these sectors plays a significant role in supplementing mitigation policies. In summary, global climate governance should determine emission reduction targets and formulate relevant systematic policies based on scientific and various emission accounting approaches, including indirect emissions. Simultaneously, it is necessary to make cities and regions more accountable for indirect emissions and establish matching interregional cooperation in emission reduction schemes and mechanisms to coordinate carbon consumption and carbon emissions. Additionally, regions need to improve their own development models through technology, industry and structure to reduce emissions within boundaries.

## Acknowledgements

This study was supported by the National Key R&D Program of China (2016YFA0602604), the Natural Science Foundation of China (71761137001, 41629501), the UK Economic and Social Research Council (ES/L016028/1), the Natural Environment Research Council (NE/N00714X/1) and a British Academy Grant (AF150310).

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