Carbon emissions of cities from a consumption perspective

Meng, Jing, Mi, Zhifu, Zheng, Jiali, Zheng, Heran, Li, Xian, Coffman, D'Maris, Woltjer, J., Wang, Shouyang and Guan, Dabo

Carbon emissions of cities from a consumption perspective

Journal: Applied Energy
Authors: Jing Meng, Zhifu Mi, Jiali Zheng, Heran Zheng, Xian Li, D'Maris Coffman, Johan Woltjer, Shouyang Wang, Dabo Guan

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 energy combustion and industrial processes for eleven cities in China in 2012 and used input-output theory to measure their consumption-based CO_2 emissions. By comprehensively comparing production- and consumption-based emissions, six developed cities were consumption-based cities with import-depended trade pattern, while the other five were production-based cities which were mostly in medium size and might transform into consumption-based cities with socioeconomic development. Emissions from imports accounted for over 50% in consumption-based emissions in most cities, which shows the significance of interregional cooperation in tackling climate change. From the perspective of final use, emissions caused by fixed capital formation occupied first in most cities, which was determined by their economic development models.

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

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 been continuing to increase in recent years. 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, which is facing tremendous ecological and environmental pressure. Therefore, actively promoting global energy conservation and emission reduction has become a world consensus in order to respond to and mitigate global climate change, accurately calculate carbon emissions in various regions by clarifying drivers, and fairly allocate the emission reduction tasks to countries and economies [1]. 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 of carbon producers and consumers.

There are two main approaches to measure carbon emissions named production-based accounting (PBA) and consumption-based accounting (CBA) [2, 3]. Currently, the most widely used carbon emission accounting approach is the PBA, which calculates the carbon emissions from the domestic production, including exports, in the producing process as the responsibility of the producer [4]. The PBA can constrain the carbon-emitting behaviour of producers and promote producers to improve energy-efficiency unit products. PBA can assist producers to address negative externalities. As this approach is widely applied in global climate change agreements, many cities calculate carbon emissions from a production perspective and compile urban greenhouse gas emission inventories to be consistent with the national-level accounting, which is conducive to horizontal comparison among cities. However, despite its obvious advantages, the PBA takes no consideration of ultimately destinations and final consumers for goods and services [5]. When promoting the development of global economy through trade redistributions [6, 7], producers and consumers of commodities will also be geographically separated due to trades, resulting in interregional emission transfer; thus, part of emission-reducing responsibilities within borders are passed on to other areas [8-10]. By excluding indirect emissions, PBA underestimates the carbon emissions in cities, as it does not depict the overall picture of urban greenhouse gas emissions [11]. If direct carbon emissions are fully borne by exporting countries, it will be clearly unfair and fail to effectively reduce CO_2 emissions [12]. Similarly, cities with low production but high consumption in China tend to be considered low-carbon [13]. The failure to include indirect emissions will lead essentially to unfair assignments of emission reduction tasks, further affect global emission reduction efficiency, and may even adversely affect the active participation in reducing emissions. Consequently, the shift of carbon emission accounting from PBA to CBA has gradually received the attention from the academy [14, 15].

Compared to PBA, the corresponding CBA has a better capability to solving the problem of unfair responsibility allocation. Based on the whole process of production, CBA calculates the total carbon emissions of final products including imports, where the responsibility for carbon emissions is borne by consumers [16]. This approach attributes direct emissions responsibilities to the final consuming sectors; consequently, it characterizes the impact of human consuming choices on climate change. First, its main advantage is to reduce carbon leakages among cities and encourage spillovers of emission-reducing technologies [17]. In addition, the index of emission per capita by CBA more realistically reflects CO_2 emission responsibilities of urban residents. At the policy level, this approach encourages restrained public consumption, 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 [18]. 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 [19-21]. As global carbon emissions calculated by CBA are also increasing every year [22], it is particularly important to analyse global carbon emissions and their influencing factors according to CBA. In general, the above studies of CBA based on the input-output analysis are relatively advantageous [17, 23], 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 the CBA to calculate carbon emissions and determine emission responsibilities at the national level, which analyses consumption-based carbon emissions at both global and national levels [24]. At a global level, research uses multi-regional input-output (MRIO) models to study emission characteristics triggered by multinational trades [12, 25-27]. At the national level, consumption-based carbon emissions are studied in many countries, including Australia [28], Japan [29], UK [30, 31], and China [13]. However, with the fast growth of China's urban population, rapid urbanization and industrialization have led to an increase in demand for energy, causing a large amount of greenhouse gas emissions [32]. Thus, cities are crucial to implement carbon emission mitigation policies in China. Research on emission inventories at the city level is limited, and mostly focuses on the PBA [11, 33-36]. Only a few studies have investigated consumption-based cities [37, 38]. Hasewaga [39] found that production-based emissions are significantly different from consumption-based emissions by constructing an MRIO table in Japan. Dhakal [40] used the CBA to analyse the carbon footprint of four Asian megacities including Beijing and Shanghai. Feng [41] studied four megacities in China by the CBA, which found that urban consumption exerted high emissions on surrounding areas through interregional trades. Given the reflections above, this study compares the CBA and PBA among cities from the perspective of carbon emission accounting. The paper aims 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. Hebei province is an appropriate representative of carbon emissions in China. It is a key example of China's economic transformation to address climate change. From the actual situation of current urbanization and industrialization in China, energy conservation and emission reduction in Hebei have achieved remarkable results. As a major industrialized province in China, Hebei province is under significant pressure for emission reductions. Large-scale development and transformation of energy resources have promoted rapid economic growth but have also led to the continuous increase of carbon emissions. The increasing carbon emissions in Hebei province, as a major 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 on industrialization and urbanization. Hence, it is essential to improve consumption structures and upgrade industrial technology in order to control the carbon emissions of Hebei province. Simultaneously, it is suitable not only for identifying similarities but also to compare between cities in Hebei province with both inland and port cities, where the development level and industrial degree of different cities in Hebei province vary widely, resulting in different energy consumption and carbon emissions among cities. 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 (CBA)

As the input-output (IO) model quantifies the network and relationship among industries in the national economy by collection of currency transactions of sectors, it has been widely applied with expansions in various aspects [42, 43], including CO_2 emissions [44-46], energy consumption [47-49], resource use [50-52] and other environmental studies [53-55]. Based on the IO model, consumption-based carbon emissions can be analysed by multi-regional input-output (MRIO) or single-regional input-output, which is used in this study [16]. More particularly, carbon emissions directly or indirectly involving the production of goods and services provided for the final use are estimated by consumer-based carbon emission accounting (CBA). In terms of environmental accounting, exogenous transactions expressed by the emission or energy are exchanged among each national sector, which represents the direct and indirect consumption of industries embodied in the final demand. In this study, the production-based carbon emissions are first measured by an IO model from production based emission inventories of Chinese cities. The consumption-based emissions adhere to the following relationship: "total consumption-based emissions = 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 [56].

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 [57]. To estimate China's CO_2 emissions CBA at the city level, the standard environmentally extended input-output method is applied in this study, whose fundamental equation known as the Leontief equation is:

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

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 consumption-based CO_2 emissions, the calculation of CO_2 emissions embodied in final demand needs the emission intensity vector *E* composed by the coefficient indicating the CO_2 emissions per unit of industrial output e_i in economic sector *i*; thus, the CO_2 emissions CBA can be estimated as follows [58, 59]:

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

where *C* denotes the vector of total CO_2 emissions embodied in the end-use goods and services for final demand, $E=[e_1e_2...e_n]$ 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* [4].

Although *C* is calculated by the total emissions embodied in the final demand, it could not separate local productions and outside imports. Since detailed import-related data is not available, the information obtained at the national level is used to estimate the CO_2 emissions embodied in imports as CBA emissions, which are briefly described by:

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

where C^{CBA} denotes the vector of total CO_2 emissions embodied in the import regarded as the consumption-based CO_2 emissions, E^{CBA} represents the row vector of national emission intensity, A^{CBA} is the technical coefficient matrix for the import, F^{CBA} directly means the import in final demand, and $\hat{F}^{CBA}=diag(F^{CBA})$ means that $\hat{F}^{CBA}$ is the diagonal vector of F^{CBA}.

It must be noted that emissions from residential energy consumption are not considered in this study.

2.2 Data sources

This article, calculating consumption-based CO_2 emissions for eleven cities in Hebei province for China, mainly requires three sets of data: 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 [60]. Data of carbon missions are not officially released in China, in which data quality of cities is relatively poor except for megacities. Consequently, a method to construct production-based CO_2 emissions inventory for cities in China is developed in this study according to the definition offered by the IPCC territorial emission accounting approach [61, 62]. Each inventory covers 47 socioeconomic sectors, 20 energy types and 9 primary industry products.

3. Results and Discussions

3.1 Consumption-based emissions for 11 cities of Hebei in China

The compositions and causes of consumption-based emissions for 11 cities of Hebei in China are analysed, which vary widely by cities but show certain regional and structural characteristics.

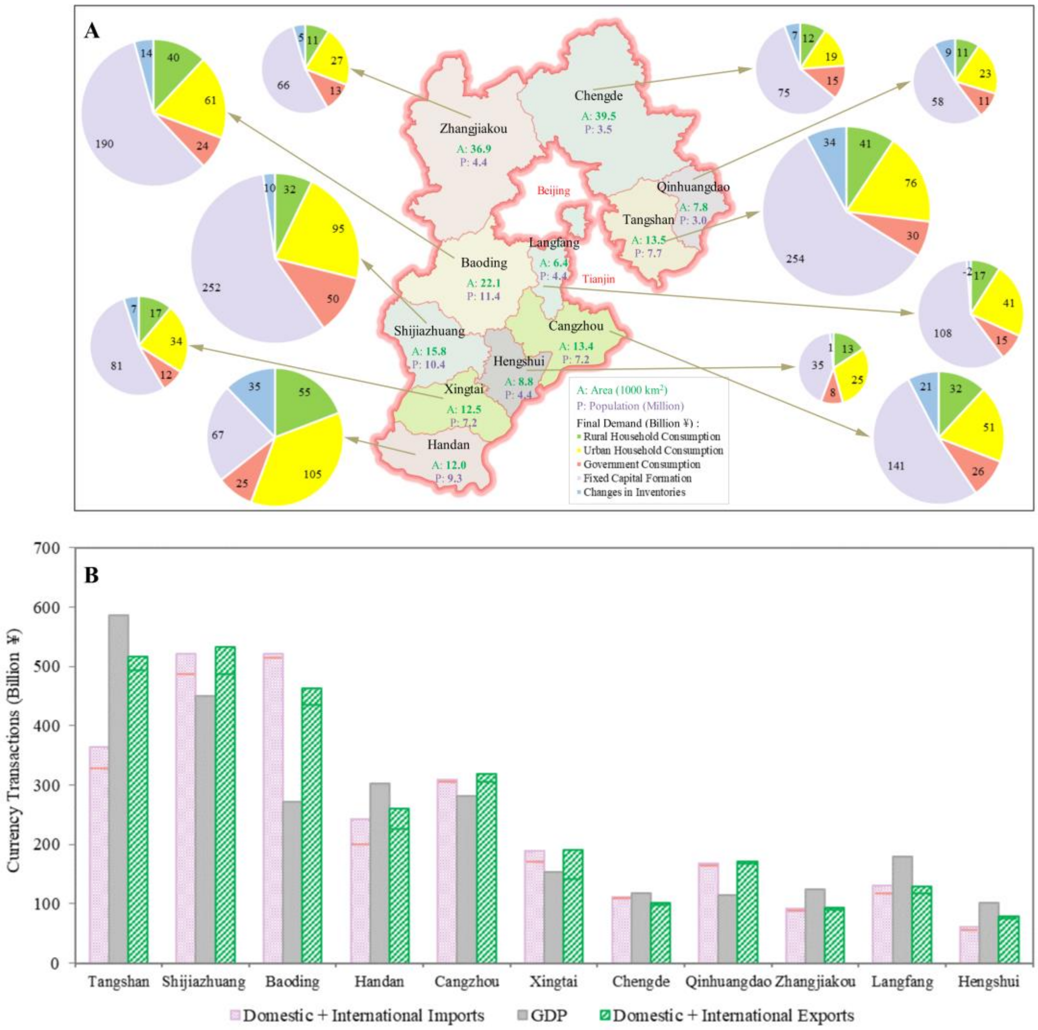

Fig. 1. (A) Socioeconomic information for 11 cities of Hebei in 2012. *A* represents the area of each city (in 1000 km^2). *P* denotes the population of each city (in Million). Total final demands are shown in the pie charts (in Billion ¥), with the five colours representing rural household consumption, urban household consumption, government consumption, fixed capital formation and changes in inventories. (B) Currency transactions for 11 cities of Hebei in 2012. Total imports (left), GDP (middle) and exports (right) are shown in the bar charts (in Billion ¥), with both domestic (down) and international (up) transactions.

Although the population density in central and southern Hebei was relatively large, with two cities in the north sparsely populated, the final demand structure with the largest contribution by the fixed capital formation was similar for each city except the southernmost Handan in 2012 (**Fig. 1A**). First of all, the population density is related to the geographic location. Cities with the smallest population density in Hebei were northern cities Chengde (89 person/km^2) and Zhangjiakou (119 person/km^2). This density characteristic is not only the result of their areas being ranked first and second, but also probably because Chengde and Zhangjiakou are bordered by Liaoning province in the China's northeast and Inner Mongolia province in the China's northwest respectively, where relative poor economic performance and massive migration in recent years affects social development and living condition. On the contrary, Baoding and Langfang benefit from geographical advantages. The former gained the largest population (11 Million) by connecting the capital Beijing to the provincial capital Shijiazhuang, and the latte,r located between two municipalities Beijing and Tianjin, features the second largest population density (691 person/km^2). Additionally, there is a certain relationship between the demand structure and the population density. Savings rates in China have remained high for a long time, which makes investment rather than consumption a major driver of domestic demand. Therefore, most cities in Hebei are characterized by, first, capital formation accounting for the largest proportion at an average of 55% of the final demand, second, urban consumption, followed by government and rural consumptions. However, the largest percentage of the final demand in Handan was the urban household consumption (105 Billion ¥, 36%) rather than the fixed capital formation (67 Billion ¥, 23%), for Handan ranked the first by population density (774 person/km^2) in Hebei.

GDP, domestic plus international imports and exports for 11 cities of Hebei in 2012 are analysed by classifying them into different types (**Fig. 1B**). The top two cities with the most GDP were the industrial centre Tangshan (586 Billion ¥) and the provincial capital Shijiazhuang (450 Billion ¥), while the city with least GDP was Hengshui (101 Billion ¥). However, the GDP in the above three cities all approximately doubled compared with that in 2007 [63]. Since the population remained almost unchanged, GDP per capita of Tangshan (76,000 ¥/person) was also the first, followed by relatively developed cities Shijiazhuang (43,000 ¥/person) and Langfang (40,000 ¥/person). By comparing final demand with imports, cities can be classified into external-depended types with the former less than the latter represented by Baoding and Qinhuangdao, and internal-oriented types with greater final demand, as represented by Tangshan and Langfang. In terms of imports and exports, currency transactions in imports and exports are similar in most cities with a few exceptions. For example, Baoding was a typical import-depended city (521 Billion ¥), while Tangshan was a typical export-oriented one (517 Billion ¥). More particularly, areas with better industrial systems preferred 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 account for no more than 2% involving Baoding (2%), Cangzhou (1%), Chengde (0.1%), Qinhuangdao (1%), Zhangjiakou (0.5%) and Hengshui (2%).

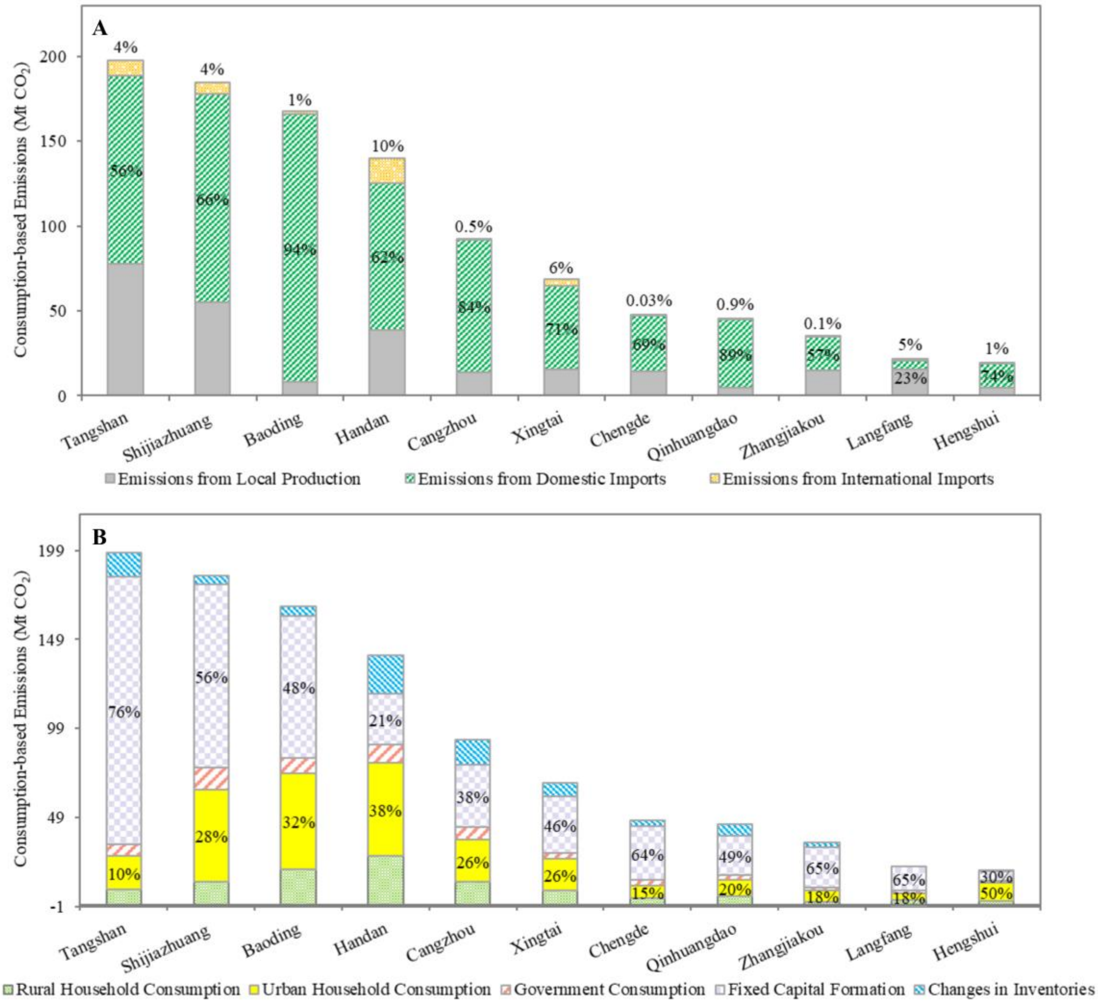

Fig. 2. (A) Consumption-based emissions from local production, domestic imports and international imports for 11 cities of Hebei in 2012. The percentages of emissions embodied in domestic and international imports are shown inside and above the bars respectively. (B) Consumption-based

emissions in five final demand categories for 11 cities of Hebei in 2012. The percentages of emissions embodied in urban household consumption and fixed capital formation are shown down and up inside the bars respectively.

The emissions caused by domestic and international imports in each city accounted for a large percentage of total consumption-based emissions including emissions embodied in total imports and emissions consumed by local products in 2012 (**Fig. 2A**). From the perspective of absolute amount, consumption-based emissions varied widely among cities in the same province, which 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) were about 10 times the consumption-based emissions of Hengshui. Furthermore, goods and services imported from elsewhere in China and foreign countries might bring more emissions than those produced and consumed within city boundaries. For instance, imports occupied more by 18% in Qinhuangdao than Langfang. Therefore, Qinhuangdao (45 Mt CO_2) emitted more than twice as much as Langfang (22 Mt CO_2) with the total consumption of Qinhuangdao (280 Billion ¥) less than that of Langfang (310 Billion ¥). From the perspective of relative proportion, imported emissions were much higher than self-produced emissions in 2012 among most cities. In 10 cities of Hebei, only with the exception of Langfang, more than 50% consumption-based emissions were caused by imports from external regions at home and abroad, which reveals that the consumption relied heavily on foreign products instead of local production. The results above are consistent with previous studies on cities showing about 70% CO_2 emissions from imports in China [63] and 40%-80% from imports in Japan [39]. According to the analysis of socioeconomic information, Baoding (95%) and Qinhuangdao (90%), the two cities ranked as the top two in terms of imported emissions percentage, corresponded with their external-depended types by imported consumption more than final demand. Similarly, Langfang (28%) and Tangshan (60%) occupied the minimum percentages of imported emissions, for they were typical internal-oriented types. More specifically, imports, as a driver of consumption-based emissions, could be further divided into domestic and international imports, which would lead to different import-emitting structures. Corresponding to analysis above, international-imported emissions accounted for at least 4% in cities preferring international imports including Tangshan (4%), Shijiazhuang (4%), Handan (10%), Xingtai (6%) and Langfang (5%); while less imports abroad resulted in emissions from international imports no more than 1% involving Baoding (1%), Cangzhou (0.5%), Chengde (0.03%), Qinhuangdao (0.9%), Zhangjiakou (0.1%) and Hengshui (1%).

Similarly, the emissions caused by fixed capital formation in each city accounted for a large percentage in total consumption-based emissions by five final demand categories including rural household consumption, urban household consumption, government consumption, fixed capital formation and changes in inventories in 2012 (**Fig. 2B**). The maximum proportion of emissions were driven by capital formation, followed by urban household consumption, in most cities in Hebei with the top three Tangshan (76%), Zhangjiakou (65%) as same as Langfang (65%), which reveals that the demand relied heavily on the investment instead of consumption. The results above are consistent with other research on CO_2 emissions in China [63-66], where development models including rapid but domestic-demand insufficient economic growth, extensive urbanization, and government-led stimulus policies are the reasons for the largest contribution from capital investment. However, urban household consumption contributed more than capital formed consumption in Handan and Hengshui as exceptions. More importantly, Handan emitted more by urban household (38%) than capital formation (21%) based on its final demand structure mentioned above, while proportions ranked differently by emissions and final demand in Hengshui mainly because of its industrial consumption structure. To be exact, the emissions caused by urban consumption (50%) occupied more than emissions from capital formation (30%) in Hengshui; however, its urban consumption percentage (30%) in the final demand is smaller than that of capital formation (43%). An underlying explanation is that the industrial sectors with high emission intensity consumed more, but invested less. For a clear explanation, Hengshui is compared with Handan, which shows a similar structure in proportion of emissions. On the one hand, since Hengshui is famous for education with highly-reputed schools, the urban household consumed above normal level in education-related industry 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 lead to more emissions under the same amount of total urban consumption. On the other hand, the capital formation did not invest 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.

3.2 Consumption-based and production-based emissions for 11 cities

Following the relationship “consumption-based emissions from local production = consumption-based emissions - emissions embodied in imports (domestic & international) = production-based emissions - emissions embodied in exports (domestic & international)”, emissions from consumption with imports and production with exports for 11 cities of Hebei in China are compared.

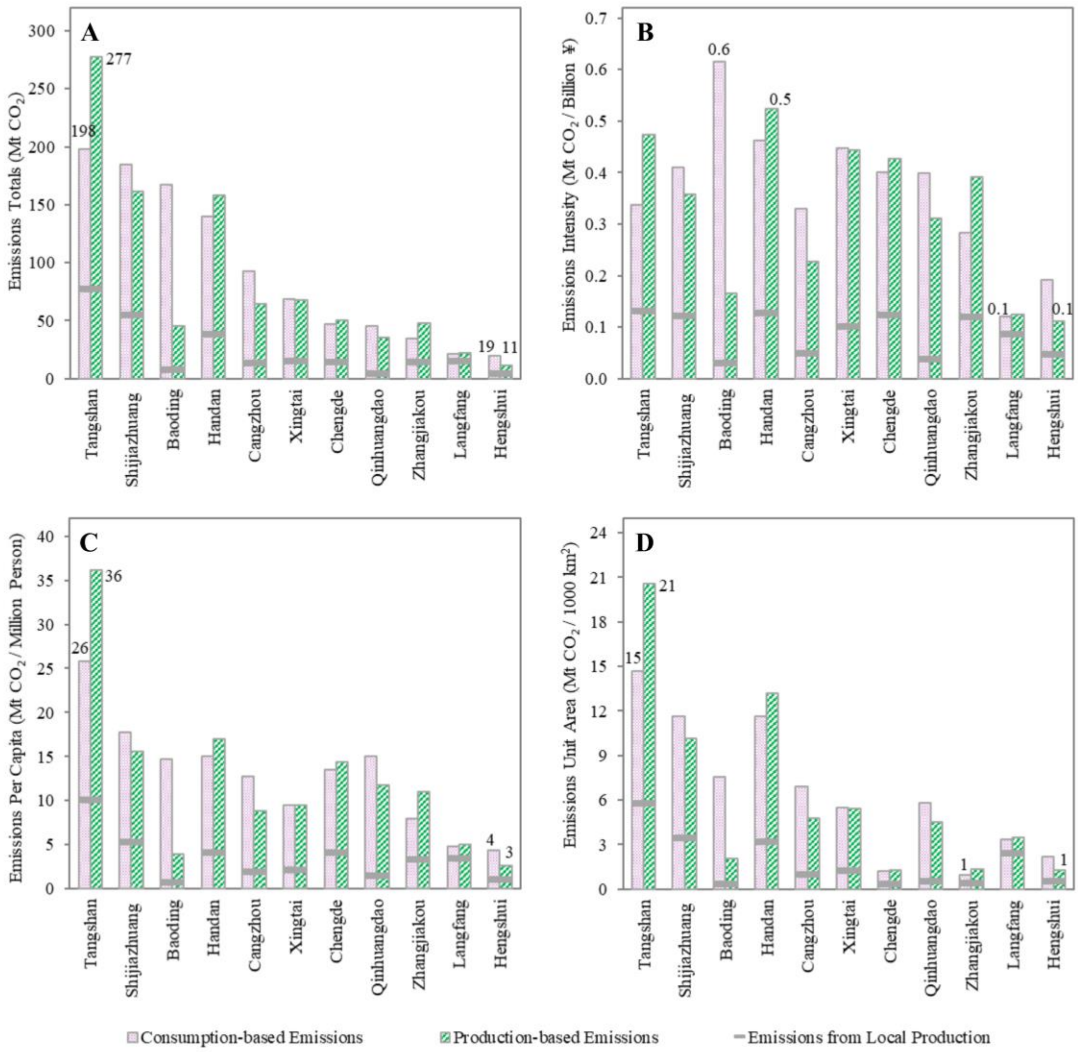

Fig. 3. (A) Total consumption-based emissions, production-based emissions and emissions from local production at the city level of Hebei in 2012. The largest and smallest emissions from consumption and production are shown above the bars respectively. (B) Consumption-based, production-based and local produced emissions intensity for 11 cities of Hebei in 2012. (C) Consumption-based, production-based

and local produced emissions per capita for 11 cities of Hebei in 2012. (D) Consumption-based, production-based and local produced emissions unit area for 11 cities of Hebei in 2012.

Cities in Hebei could be categorized into consumption-based cities and production-based cities with great differences in source of emissions (**Fig. 3A**), which was mainly caused by the trade pattern and emission intensity [67, 68]. First, Shijiazhuang, Baoding, Cangzhou, Xingtai, Qinhuangdao and Hengshui named consumption-based cities had consumption-based emissions higher than production-based emissions. According to above two causes, Baoding, as a typical import-depended city analysed in *3.1*, was classified into consumption-based type mainly due to its trade pattern with emissions from consumption (168 Mt CO_2) almost four times the amount of production-based emissions (45 Mt CO_2). Simultaneously, Qinhuangdao, as an example with similar imports and exports, became a consumption-base city with consumed emissions (45 Mt CO_2) more than produced emissions (35 Mt CO_2) because of its high emission intensity of imports (0.4 Mt CO_2/Billion ¥). Second, production-based cities with larger emissions from exports than imports included Tangshan, Handan, Chengde, Zhangjiakou and Langfang. Similarly, the typical export-oriented trade pattern lead to production-based emissions (277 Mt CO_2) larger than consumption-based emissions (198 Mt CO_2) in Tangshan; and the import-export equalled Zhangjiakou emitted more in production (48 Mt CO_2) than consumption (35 Mt CO_2) caused by high emission intensity of exports (0.4 Mt CO_2/Billion ¥). Furthermore, the findings reveal that there is a large gap between consumption-based accounting (CBA) and production-based accounting (PBA), which demonstrates that PBA benefited consumption-based cities in allocating responsibilities. Thus, production-based cities have proposed to widely apply CBA for climate change mitigation. Notably, 5 production-based cities of Hebei in the above results were consistent with the conclusion that most medium-sized cities were production-based cities [63]. Besides, by using cities with both commons and differences within one province as better samples, the finding stating that most developed cities in China were consumption-based cities in [63] was expanded to both developed and less developed regions. In fact, the former was proved to be caused by the largely-imported trade pattern; while the latter mostly imported consumption with high emission intensity, which might be owing to its unimproved technology or primary industries. Better still, Shijiazhuang had transformed from a production-based city in 2007 to a consumption-based city in 2012 by its rapid economic development as the provincial capital of

Hebei, which could be an evidence of the inference in [63].

The gap of total production-based emissions between the largest emitter Tangshan (277 Mt CO_2) and smallest emitter Hengshui (11 Mt CO_2) was approximately 25 times, which was much more substantial than that of consumption-based emissions (10 times). However, only Hengshui (0.1 Mt CO_2/Billion ¥) remained at the same ranking for production-based emissions intensity. Langfang (0.1 Mt CO_2/Billion ¥) replaced Hengshui with the lowest consumption-based emissions intensity. Simultaneously, Baoding (0.6 Mt CO_2/Billion ¥) and Handan (0.5 Mt CO_2/Billion ¥) ranked first in consumption-based and production-based emissions intensity, respectively (**Fig. 3B**). Adjusted by per unit GDP, the differences among cities in consumption-based, production-based and local produced emissions all reduced with emissions intensity of local production basically divided into two groups by around 0.1 (Mt CO_2/Billion ¥) or below, 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 Chengde, Qinhuangdao and Zhangjiakou in the north with relatively sparse populations were slightly rising compared with total emissions (**Fig. 3C**). Besides PBA, per capita accounting was relatively fair when allocating responsibilities. Similarly, with regard to emissions unit area, the large area of Zhangjiakou resulted in the smallest consumption-based emissions unit area with rankings of Tangshan and Hengshui still remaining (**Fig. 3D**). Hence, different accounting approaches with various criteria should be considered comprehensively in identifying fair mitigation policies.

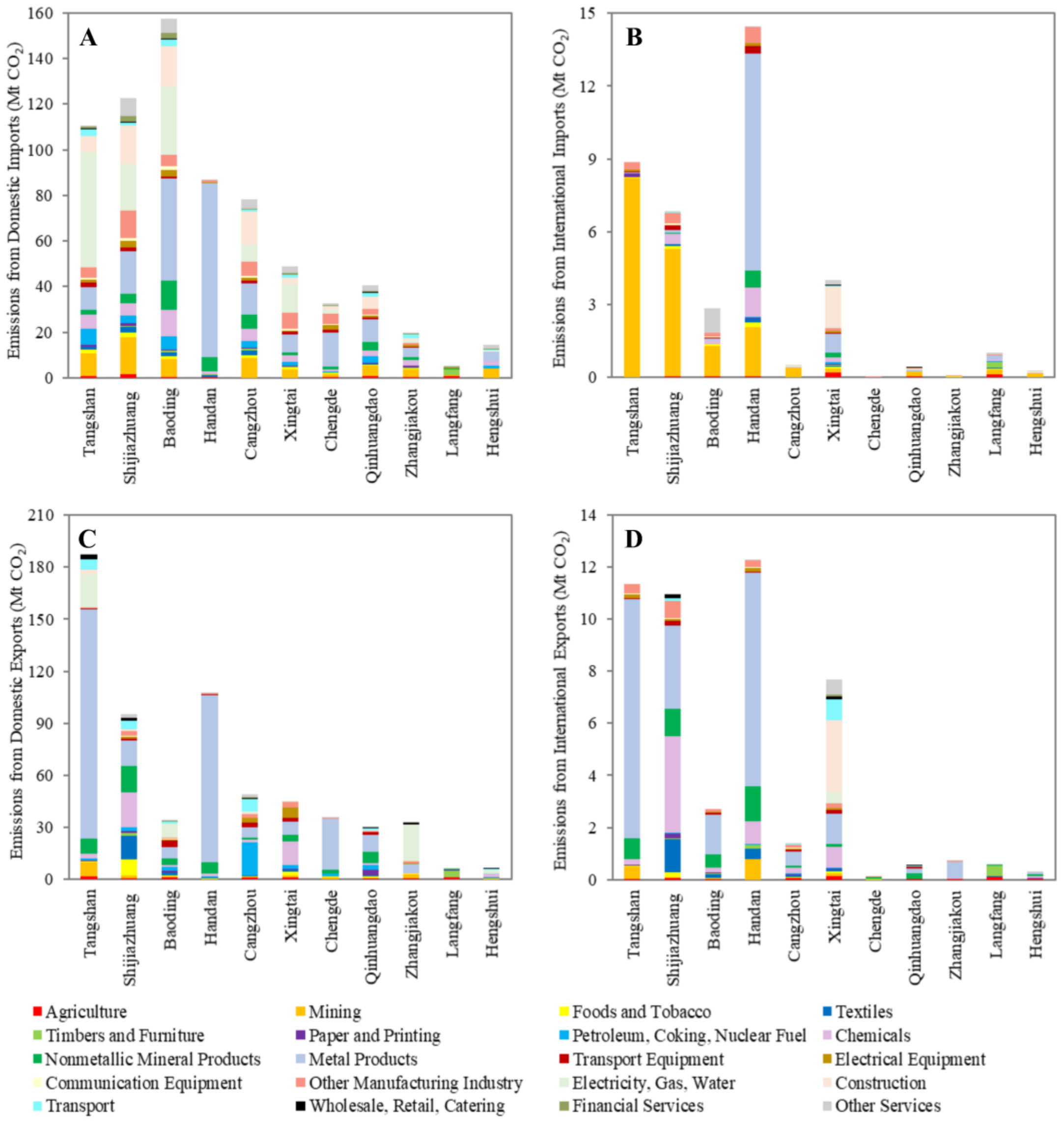

Fig. 4. (A) CO_2 emissions embodied in domestic imports by sectors for 11 cities of Hebei in 2012. (B) CO_2 emissions embodied in international imports by sectors for 11 cities of Hebei in 2012. (C) CO_2 emissions embodied in domestic exports by sectors for 11 cities of Hebei in 2012. (D) CO_2 emissions embodied in international exports by sectors for 11 cities of Hebei in 2012.

Emissions embodied in imports and exports were determined by the volume of imports and exports and consumption structure, where more emissions were caused by the increasing consumption in sectors with high emission intensity. In domestic imports, domestic imports of Baoding (512 Billion ¥) were the first resulting in the largest 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) with its domestic imports (112 Billion ¥) slightly less than those of the latter (116 Billion ¥) (**Fig. 4A**). Similarly, in international imports, Handan was the first in emissions from international imports (14 Mt CO_2) because it has most international imports (43 Billion ¥). Emissions embodied in international imports of Tangshan (9 Mt CO_2) were slightly higher than those of Shijiazhuang (7 Mt CO_2), which corresponded to international imports in the former (36 Billion ¥) and the latter (35 Billion ¥) due to the similar structure of sectoral consumption (**Fig. 4B**). In terms of domestic exports, contrary to international imports, 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) with domestic exports ranked first in the former (494 Billion ¥) close to the latter (486 Billion ¥). This might be caused by the heavy industrial system in Tangshan, which, for historical reasons can be compared with Shijiazhuang with its upgraded industrial structure in the period 2007-2012 (**Fig. 4C**). Different from the findings above, in international exports, sectors in Xingtai produced less emissions with the system focusing on tertiary industry, while international exports were the most. However, Handan, Tangshan and Shijiazhuang are the top three of emissions from international exports owing to their massive emissions in sectors with high emission represented by metal products (**Fig. 4D**).

In general, the sector of metal products contributed most to emissions, which were consistent with previous research [63]. Therefore, Hebei still needs to improve technology, upgrade industry, and transform structure. Horizontally compared domestic and international emissions, domestic totals both in imports and exports were much larger than international totals. Moreover, domestic emissions in each city were successively decreasing, while international emissions were concentrated in the maximum and minimum extremes with a sizeable gap. When imported and exported emissions are vertically compared, then the relative size of total imports and exports corresponded to the type of city that is consumption-based or production-based. Meanwhile, as most cities in Hebei prefer the secondary industrial system, the proportion of the tertiary industry in emissions from imports was greater than that in emissions from exports. More specifically, emissions from domestic and international imports varied widely among sectors, in which emissions from domestic imports were mostly embodied in electricity, gas, water and metal sectors while emissions from international imports occupied most in mining. This is because goods and services from other regions at home basically show 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 ones. 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 both concentrating in metal products. This is determined by 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 great impact on issues of allocating responsibilities for climate change mitigation. In the analysis, CO_2 emissions for 11 cities of Hebei in China are measured by CBA compared with PBA to identify fair mitigation policies. Based on different consumption structures including final demand plus domestic and international imports, cities not only emit within boundaries but also absorb carbon by interregional trades. Final demand is relatively large in internally-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 with a large population density. In addition, the consumption structure will also influence externally 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 use. According to a range of socioeconomic factors, different drivers cause different compositions of emissions among cities.

In consumption-based emissions, imported emissions from domestic and international goods and services in 11 cities are much higher than self-produced emissions embodied in local products, accounting for typically a large percentage of more than 50%. From the perspective of imported proportions in emissions, the consumption at the city level is mostly determined by products from other regions and foreign countries rather than local production. Therefore, both national systems in China and global mechanisms among economies are generallyestablished through policies aimed at strengthening cooperation between consuming and producing regions to mitigate climate change. In terms of consumption-based emissions caused by trades 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 contributed to coordinate production relations, balance emission shares, strengthen synergistic effects, and mitigate aggregate changes in China. Besides, the interregional clean development mechanism (CDM) in China would promote cities or provinces with cleaner production to merchandise carbon emission permits by investing in less developed regions or areas for improved technologies and upgraded industries. Better still, the design and operation of mechanisms in international organizations or developed countries, represented by the European Union Emissions Trading System (EU ETS), have been more advanced by improvement with more practice, which played an important role in coordinating global actions of carbon emissions and climate change among countries. Excellent international or regional mechanisms should not only be used as references and examples of best practice, but should also establish active and widely distributed involvement. Similarly, the emissions caused by fixed capital formation in most cities of Hebei account for the largest proportion, with the urban consumption as the second, followed by government and rural consumptions in total consumption-based emissions in 2012, which shows that the demand is predominantly driven by investment rather than consumption in China, due to high rate savings. Taking Hebei as an example, compositions of emissions are determined by structures of both final demand and industrial consumption in China, for cities emit less by consuming or investing in sectors with low emission intensity. By encouraging demand and accelerating urbanization, final demand structures in China will shift from capital investment and rural consumption to urban household consumption, respectively. Simultaneously, consumption structures in China will likely transition from high emission sectors to low-carbon industries with technical and model improvement in economic development.

By comparing emissions from imports, exports and local production for 11 cities of Hebei, cities in China can be categorized into consumption-based cities and production-based cities, depending on the source of emissions. Since trade pattern and emission intensity are the main causes of different types, the 6 consumption-based cities including Shijiazhuang, Baoding, Cangzhou, Xingtai, Qinhuangdao and Hengshui are typical import-dependent cities of 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. These cities are typical export-oriented types with high emission intensities from exports. Thus, 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 metropolis. 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 by per GDP, capita or area to fairly allocate responsibilities.

In general, the activity of reducing emissions is closely related to industry upgrade and structure transformation in China. Cities emit less through importing or exporting in sectors with low emission intensities. For instance, the sector of metal products contributed most to emissions from imports and exports in Hebei. Hence, technology improvement in these sectors play a significant role in identifying fair mitigation policies. In summary, global climate governance should determine emission reduction targets and build relevant systematic policies based on scientific and fair 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 by 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), Natural Environment Research Council (NE/N00714X/1) and British Academy Grant (AF150310).

References

[1] Kagawa S, Suh S, Hubacek K, Wiedmann T, Nansai K, Minx J. CO_2 emission clusters within global supply chain networks: Implications for climate change mitigation. Global Environmental Change. 2015;35:486-96.
[2] Shigeto S, Yamagata Y, Ii R, Hidaka M, Horio M. An easily traceable scenario for 80% CO_2 emission reduction in Japan through the final consumption-based CO_2 emission approach: A case study

of Kyoto-city. Applied Energy. 2012;90:201-5.
[3] Zhang B, Qiao H, Chen Z, Chen B. Growth in embodied energy transfers via China's domestic trade: Evidence from multi-regional input-output analysis. Applied energy. 2016;184:1093-105.
[4] Peters GP. From production-based to consumption-based national emission inventories. Ecological economics. 2008;65:13-23.
[5] Steininger K, Lininger C, Droege S, Roser D, Tomlinson L, Meyer L. Justice and cost effectiveness of consumption-based versus production-based approaches in the case of unilateral climate policies. Global Environmental Change. 2014;24:75-87.
[6] Lin B, Sun C. Evaluating carbon dioxide emissions in international trade of China. Energy policy. 2010;38:613-21.
[7] Chen G, Wiedmann T, Wang Y, Hadjikakou M. Transnational city carbon footprint networks-Exploring carbon links between Australian and Chinese cities. Applied energy. 2016;184:1082-92.
[8] Weber CL, Matthews HS. Embodied environmental emissions in US international trade, 1997-2004. ACS Publications; 2007.
[9] Scott K, Barrett J. An integration of net imported emissions into climate change targets. Environmental Science & Policy. 2015;52:150-7.
[10] Arce G, López LA, Guan D. Carbon emissions embodied in international trade: The post-China era. Applied energy. 2016;184:1063-72.
[11] Hoornweg D, Sugar L, Trejos Gomez CL. Cities and greenhouse gas emissions: moving forward. Environment and Urbanization. 2011;23:207-27.
[12] Davis SJ, Caldeira K. Consumption-based accounting of CO_2 emissions. Proceedings of the National Academy of Sciences. 2010;107:5687-92.
[13] Feng K, Davis SJ, Sun L, Li X, Guan D, Liu W, et al. Outsourcing CO_2 within China. Proceedings of the National Academy of Sciences. 2013;110:11654-9.
[14] Yang Z, Wei T, Moore J, Chou J, Dong W, Dai R, et al. A new consumption-based accounting model for greenhouse gases from 1948 to 2012. Journal of Cleaner Production. 2016;133:368-77.
[15] Hu Y, Lin J, Cui S, Khanna NZ. Measuring urban carbon footprint from carbon flows in the global supply chain. Environmental science & technology. 2016;50:6154-63.
[16] Wiedmann T. A review of recent multi-region input-output models used for consumption-based emission and resource accounting. Ecological Economics. 2009;69:211-22.
[17] Peters GP, Hertwich EG. Post-Kyoto greenhouse gas inventories: production versus consumption. Climatic Change. 2008;86:51-66.
[18] Larsen HN, Hertwich EG. Identifying important characteristics of municipal carbon footprints. Ecological Economics. 2010;70:60-6.
[19] Du H, Guo J, Mao G, Smith AM, Wang X, Wang Y. CO_2 emissions embodied in China-US trade: Input-output analysis based on the emergy/dollar ratio. Energy Policy. 2011;39:5980-7.
[20] Wu R, Geng Y, Dong H, Fujita T, Tian X. Changes of CO_2 emissions embodied in China-Japan trade: drivers and implications. Journal of Cleaner Production. 2016;112:4151-8.
[21] Jayanthakumaran K, Liu Y. Bi-lateral CO_2 emissions embodied in Australia-China trade. Energy Policy. 2016;92:205-13.
[22] Xu Y, Dietzenbacher E. A structural decomposition analysis of the emissions embodied in trade. Ecological Economics. 2014;101:10-20.
[23] Steininger KW, Lininger C, Meyer LH, Muñoz P, Schinko T. Multiple carbon accounting to

support just and effective climate policies. Nature Climate Change. 2016;6:35.
[24] Tian X, Chang M, Lin C, Tanikawa H. China's carbon footprint: a regional perspective on the effect of transitions in consumption and production patterns. Applied energy. 2014;123:19-28.
[25] Peters GP, Hertwich EG. CO_2 embodied in international trade with implications for global climate policy. ACS Publications; 2008.
[26] Hertwich EG, Peters GP. Carbon footprint of nations: A global, trade-linked analysis. Environmental science & technology. 2009;43:6414-20.
[27] Peters GP, Minx JC, Weber CL, Edenhofer O. Growth in emission transfers via international trade from 1990 to 2008. Proceedings of the national academy of sciences. 2011:201006388.
[28] Wood R, Dey CJ. Australia's carbon footprint. Economic Systems Research. 2009;21:243-66.
[29] Nansai K, Kagawa S, Kondo Y, Suh S, Inaba R, Nakajima K. Improving the completeness of product carbon footprints using a global link input-output model: the case of Japan. Economic Systems Research. 2009;21:267-90.
[30] Wiedmann T, Wood R, Minx JC, Lenzen M, Guan D, Harris R. A carbon footprint time series of the UK-results from a multi-region input-output model. Economic systems research. 2010;22:19-42.
[31] Barrett J, Peters G, Wiedmann T, Scott K, Lenzen M, Roelich K, et al. Consumption-based GHG emission accounting: a UK case study. Climate Policy. 2013;13:451-70.
[32] Wei Y, Liu L, Wu G, Zou L. Energy economics: CO_2 emissions in China: Springer Science & Business Media; 2011.
[33] Dhakal S. Urban energy use and carbon emissions from cities in China and policy implications. Energy policy. 2009;37:4208-19.
[34] Sugar L, Kennedy C, Leman E. Greenhouse gas emissions from Chinese cities. Journal of Industrial Ecology. 2012;16:552-63.
[35] Liu Z, Liang S, Geng Y, Xue B, Xi F, Pan Y, et al. Features, trajectories and driving forces for energy-related GHG emissions from Chinese mega cites: the case of Beijing, Tianjin, Shanghai and Chongqing. Energy. 2012;37:245-54.
[36] Creutzig F, Baiocchi G, Bierkandt R, Pichler P-P, Seto KC. Global typology of urban energy use and potentials for an urbanization mitigation wedge. Proceedings of the National Academy of Sciences. 2015;112:6283-8.
[37] Fan J, Guo X, Marinova D, Wu Y, Zhao D. Embedded carbon footprint of Chinese urban households: structure and changes. Journal of cleaner Production. 2012;33:50-9.
[38] Minx J, Baiocchi G, Wiedmann T, Barrett J, Creutzig F, Feng K, et al. Carbon footprints of cities and other human settlements in the UK. Environmental Research Letters. 2013;8:035039.
[39] Hasegawa R, Kagawa S, Tsukui M. Carbon footprint analysis through constructing a multi-region input-output table: a case study of Japan. Journal of Economic Structures. 2015;4:5.
[40] Dhakal S. Urban energy use and greenhouse gas emissions in Asian mega-cities. Institute for Global Environmental Strategies, Kitakyushu, Japan. 2004.
[41] Feng K, Hubacek K, Sun L, Liu Z. Consumption-based CO_2 accounting of China's megacities: the case of Beijing, Tianjin, Shanghai and Chongqing. Ecological Indicators. 2014;47:26-31.
[42] Minx JC, Wiedmann T, Wood R, Peters GP, Lenzen M, Owen A, et al. Input-output analysis and carbon footprinting: an overview of applications. Economic Systems Research. 2009;21:187-216.
[43] Wiedmann T. Carbon footprint and input-output analysis-an introduction. Taylor & Francis; 2009.
[44] Su B, Ang B. Input-output analysis of CO_2 emissions embodied in trade: a multi-region model for China. Applied Energy. 2014;114:377-84.

[45] Mi Z-F, Pan S-Y, Yu H, Wei Y-M. Potential impacts of industrial structure on energy consumption and CO_2 emission: a case study of Beijing. Journal of Cleaner Production. 2015;103:455-62.
[46] Yan J, Zhao T, Kang J. Sensitivity analysis of technology and supply change for CO_2 emission intensity of energy-intensive industries based on input-output model. Applied energy. 2016;171:456-67.
[47] Yuan C, Liu S, Xie N. The impact on chinese economic growth and energy consumption of the Global Financial Crisis: An input-output analysis. Energy. 2010;35:1805-12.
[48] Cellura M, Di Gangi A, Longo S, Orioli A. An Italian input-output model for the assessment of energy and environmental benefits arising from retrofit actions of buildings. Energy and Buildings. 2013;62:97-106.
[49] Wei Y-M, Mi Z-F, Huang Z. Climate policy modeling: an online SCI-E and SSCI based literature review. Omega. 2015;57:70-84.
[50] Weinzettel J, Hertwich EG, Peters GP, Steen-Olsen K, Galli A. Affluence drives the global displacement of land use. Global Environmental Change. 2013;23:433-8.
[51] Yu Y, Hubacek K, Feng K, Guan D. Assessing regional and global water footprints for the UK. Ecological Economics. 2010;69:1140-7.
[52] Wiedmann TO, Schandl H, Lenzen M, Moran D, Suh S, West J, et al. The material footprint of nations. Proceedings of the National Academy of Sciences. 2013:201220362.
[53] Lenzen M, Moran D, Kanemoto K, Foran B, Lobefaro L, Geschke A. International trade drives biodiversity threats in developing nations. Nature. 2012;486:109.
[54] Lin J, Pan D, Davis SJ, Zhang Q, He K, Wang C, et al. China's international trade and air pollution in the United States. Proceedings of the National Academy of Sciences. 2014;111:1736-41.
[55] Yang S, Fath B, Chen B. Ecological network analysis of embodied particulate matter 2.5-A case study of Beijing. Applied energy. 2016;184:882-8.
[56] Rocco MV, Colombo E. Evaluating energy embodied in national products through Input-Output analysis: Theoretical definition and practical application of international trades treatment methods. Journal of cleaner production. 2016;139:1449-62.
[57] Leontief WW. Quantitative input and output relations in the economic systems of the United States. The review of economic statistics. 1936:105-25.
[58] Mi Z, Meng J, Guan D, Shan Y, Song M, Wei Y-M, et al. Chinese CO_2 emission flows have reversed since the global financial crisis. Nature communications. 2017;8:1712.
[59] Mi Z, Meng J, Green F, Coffman DM, Guan D. China's "exported carbon" peak: patterns, drivers, and implications. Geophysical Research Letters. 2018;45:4309-18.
[60] NBSC. National data. 2015;<http://data.stats.gov.cn/english/> [accessed 2015-02-01].
[61] Mi Z-F, Wei Y-M, He C-Q, Li H-N, Yuan X-C, Liao H. Regional efforts to mitigate climate change in China: a multi-criteria assessment approach. Mitigation and Adaptation Strategies for Global Change. 2017;22:45-66.
[62] Shan Y, Guan D, Liu J, Liu Z, Liu J, Schroeder H, et al. CO_2 emissions inventory of Chinese cities. Atmos Chem Phys. 2016.
[63] Mi Z, Zhang Y, Guan D, Shan Y, Liu Z, Cong R, et al. Consumption-based emission accounting for Chinese cities. Applied energy. 2016;184:1073-81.
[64] Peters GP, Weber CL, Guan D, Hubacek K. China's growing CO_2 emissions a race between increasing consumption and efficiency gains. ACS Publications; 2007.
[65] Guan D, Peters GP, Weber CL, Hubacek K. Journey to world top emitter: An analysis of the driving forces of China's recent CO_2 emissions surge. Geophysical Research Letters. 2009;36.

[66] Feng K, Siu YL, Guan D, Hubacek K. Analyzing drivers of regional carbon dioxide emissions for China: A structural decomposition analysis. Journal of Industrial Ecology. 2012;16:600-11.
[67] Jakob M, Marschinski R. Interpreting trade-related CO_2 emission transfers. Nature Climate Change. 2013;3:19.
[68] López L-A, Arce G, Zafrilla J. Financial crisis, virtual carbon in global value chains, and the importance of linkage effects. The Spain-China case. Environmental science & technology. 2013;48:36-44.