

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/304395807>

Consumption-based emission accounting for Chinese cities

Article in *Applied Energy* · June 2016

DOI: 10.1016/j.apenergy.2016.06.094

READS

127

8 authors, including:



Dabo Guan

University of East Anglia

101 PUBLICATIONS 3,273 CITATIONS

SEE PROFILE



Yuli Shan

University of East Anglia

6 PUBLICATIONS 11 CITATIONS

SEE PROFILE



Zhu Liu

Harvard University

45 PUBLICATIONS 943 CITATIONS

SEE PROFILE



Rong-Gang Cong

Aarhus University

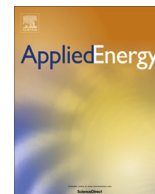
30 PUBLICATIONS 446 CITATIONS

SEE PROFILE



Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Consumption-based emission accounting for Chinese cities

Zhifu Mi^a, Yunkun Zhang^a, Dabo Guan^{a,*}, Yuli Shan^a, Zhu Liu^b, Ronggang Cong^c, Xiao-Chen Yuan^{d,e}, Yi-Ming Wei^{d,e}

^a Tyndall Centre for Climate Change Research, School of International Development, University of East Anglia, Norwich NR4 7TJ, UK

^b Applied Physics and Materials Science, California Institute of Technology Resnick Sustainability Institute, Pasadena, CA 91125, USA

^c Department of Environmental Science, Aarhus University, Roskilde 4000, Denmark

^d Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China

^e School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China

HIGHLIGHTS

- We calculate consumption-based CO₂ emissions for thirteen Chinese cities.
- Substantial differences exist between production- and consumption-based accounting.
- 70% of consumption-based emissions are imported from other regions in Chinese megacities.
- Capital formation is the largest contributor to consumption-based emissions.
- Production-based cities tend to become consumption-based as they undergo socioeconomic development.

ARTICLE INFO

Article history:

Received 28 March 2016

Received in revised form 13 June 2016

Accepted 18 June 2016

Available online xxxxx

Keywords:

Consumption-based accounting

Production-based emissions

Embodied emissions

Input–output analysis

Carbon footprint

City

ABSTRACT

Most of China's CO₂ emissions are related to energy consumption in its cities. Thus, cities are critical for implementing China's carbon emissions mitigation policies. In this study, we employ an input-output model to calculate consumption-based CO₂ emissions for thirteen Chinese cities and find substantial differences between production- and consumption-based accounting in terms of both overall and per capita carbon emissions. Urban consumption not only leads to carbon emissions within a city's own boundaries but also induces emissions in other regions via interregional trade. In megacities such as Shanghai, Beijing and Tianjin, approximately 70% of consumption-based emissions are imported from other regions. Annual per capita consumption-based emissions in the three megacities are 14, 12 and 10 tonnes of CO₂ per person, respectively. Some medium-sized cities, such as Shenyang, Dalian and Ningbo, exhibit per capita emissions that resemble those in Tianjin. From the perspective of final use, capital formation is the largest contributor to consumption-based emissions at 32–65%. All thirteen cities are categorized by their trading patterns: five are production-based cities in which production-based emissions exceed consumption-based emissions, whereas eight are consumption-based cities, with the opposite emissions pattern. Moreover, production-based cities tend to become consumption-based as they undergo socioeconomic development.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

China has been the world's largest producer of CO₂ emissions since 2007. In 2013, its CO₂ emissions from fuel combustion totalled 8.5 billion tonnes, which accounted for a quarter of global CO₂ emissions [1,2]. China has prioritized climate change mitigation in the past decade, announcing in the 2014 “U.S.–China Joint Announcement on Climate Change” that its CO₂ emissions will

peak by 2030. In addition, in its 2015 Intended Nationally Determined Contributions, China promised to decrease its CO₂ emissions per unit of GDP by 60–65% (based on 2005 levels) by 2030 [3].

Accompanying its rapid economic growth, China's urban population has increased dramatically during recent decades. The urban population grew to 750 million in 2014, increasing from approximately 300 million in 1990. Today, more than half of China's population lives in cities [4]. This rapid urbanization and industrialization have led to increased demands for energy and materials, which result in substantial emissions of greenhouse gases (GHG), including CO₂ [5,6]. Approximately 85% of China's

* Corresponding author.

E-mail address: dabo.guan@uea.ac.uk (D. Guan).

CO₂ emissions are related to urban energy consumption, a rate that is much higher than that experienced in Europe (69%) or in the U.S. (80%) [7,8]. Therefore, cities are critical for implementing China's carbon emissions mitigation policies. There is an urgent need to understand China's urban CO₂ emissions, as such understanding is fundamental to proposing mitigation actions.

There are two approaches to measuring GHG emissions: production-based and consumption-based accounting [9–11]. Production-based CO₂ emissions are emissions caused by domestic production, including exports [12]. This approach accounts for CO₂ emissions at the point of production, without consideration of where goods are used or who ultimately uses them [13,14]. This approach is widely used in global climate change agreements, including the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. Conversely, under consumption-based accounting, all emissions occurring along the chains of production and distribution are allocated to the final consumers of products [15]. Pursuant to this approach, areas that import products are allocated the emissions related to their production. Therefore, consumption-based emissions include imports and emissions embodied in trade but exclude exports, whereas production-based emissions include exports and exclude imports [12]. Recent studies have compared the two approaches and demonstrated the advantages of consumption-based accounting [16–19]. For example, Steininger et al. [13] argued that a consumption-based climate policy approach can improve both cost-effectiveness and justice, while Guan et al. [20] indicated that consumption-based accounting helps mitigate global air pollution. Moreover, Larsen and Hertwich [21] argued that consumption-based accounting provides a more useful and less misleading indicator for assessing the performance of local climate actions. Finally, Peters and Hertwich [22] have noted that consumption-based accounting has many advantages over production-based accounting, such as addressing carbon leakage, promoting environmental comparative advantages, increasing options for mitigation, and encouraging technology diffusion.

There are numerous studies on consumption-based carbon emissions at the global and national levels [23]. Peters and Hertwich [22] calculated CO₂ emissions embodied in international trade among 87 countries. They found that 53 billion tonnes of CO₂ emissions in 2001 were embodied in international trade and that developed countries were net importers of emissions. Hertwich and Peters [24] quantified consumption-based greenhouse gas emissions for 73 nations and 14 aggregated world regions. At the global level in 2001, 72% of greenhouse gas emissions were related to household consumption, 18% to investment and 10% to government consumption. Davis and Caldeira [25] used a fully coupled multi-region input-output (MRIO) model to construct a consumption-based CO₂ emissions inventory of 113 countries and regions. The results showed that 62 billion tonnes of CO₂ were traded internationally, which accounted for 23% of global emissions. These CO₂ emissions were mainly exported from China and other emerging markets to developed countries. Peters et al. [26] developed a global database for consumption-based CO₂ emissions for 113 countries. In most developed countries, consumption-based emissions increased faster than territorial production-based emissions. Under consumption-based accounting, net CO₂ emissions transferred from developing countries to developed countries grew from 4 billion tonnes in 1990 to 16 billion tonnes in 2008.

At the national level, Wood and Dey [27] applied a consumption-based approach to calculating Australia's carbon footprint and found that emissions embodied in exports were much higher than those embodied in imports and that Australia's total carbon footprint was 522 million tonnes (Mt) in 2005. Nansai et al. [28] applied a global link input-output model to analyse

Japan's carbon footprint. Wiedmann et al. [29] and Barrett et al. [30] both calculated the UK's consumption-based greenhouse gas emissions and found that consumption-based carbon emissions were rapidly increasing and that there was a widening gap between production- and consumption-based emissions. Feng et al. [31] tracked carbon emissions embodied in products in the Chinese provinces; these authors found that 57% of total emissions were related to goods and services that were used outside of the province in which they were produced. For example, 80% of the emissions embodied in goods used in the highly developed coastal provinces were imported from less developed areas.

Studies of emission inventories for cities are limited, and most are focused on production-based accounting. Dhakal [8] compiled energy usage and emissions inventories for 35 provincial capital cities in China. The results showed that these 35 cities accounted for 40% of China's energy consumption and CO₂ emissions and that the carbon intensity for these cities decreased throughout the 1990s. Hoorweg et al. [32] analysed per capita GHG emissions for several large cities and reviewed emissions for 100 cities. They showed that annual per capita emissions for cities varied from more than 15 tonnes of CO₂ equivalent to less than half a tonne. Sugar et al. [33] provided detailed GHG emission inventories for Beijing, Shanghai and Tianjin and found that Chinese cities are among the world's highest per capita emitters when compared with ten other global cities. Liu et al. [34] analysed features, trajectories and driving forces of GHG emissions in four Chinese megacities (Beijing, Tianjin, Shanghai and Chongqing) from 1995 to 2009. The emission inventories compiled in this paper include both direct emissions and emissions from imported electricity. Creutzig [35] used data from 274 cities to explore the potential for urban mitigation of global climate change. The results showed that urban energy use will grow threefold between 2005 and 2050, if current trends in urban expansion continue.

Few studies have researched consumption-based emissions for cities [36,37]. Hasegawa et al. [38] constructed a multi-region input-output table among 47 prefectures in Japan and estimated their consumption-based carbon emissions. They found that production-based emissions differed great from consumption-based emissions. Moreover, the ratio of carbon leakage to carbon footprint was more than 50% on average at the regional level. Almost all previous studies of consumption-based emissions in Chinese cities focus on the same four megacities, i.e., Beijing, Shanghai, Tianjin and Chongqing. Dhakal [39] used a consumption-based approach to analyse the carbon footprints of four Asian megacities, including Beijing and Shanghai. Feng et al. [40] also analysed consumption-based carbon emissions in the four Chinese megacities and found that urban consumption imposed high emissions on surrounding regions via interregional trade. In this study, we use an input-output model to construct consumption-based CO₂ emissions for thirteen Chinese cities.

2. Method and data

2.1. Input-output model for consumption-based accounting of carbon emissions

The input-output model is one of the most widely used methods of analysing consumption-based carbon emissions [41]. The method is divided into single-region input-output and multi-region input-output (MRIO). In this study, we use the single-region input-output model. Some studies have summarized the input-output model and its applications [42,43]. Dietzenbacher et al. [44] compiled eight experts' views on the future of input-output. As mentioned above, the method has been widely used in environmental research [45] on energy consumption [46–48],

greenhouse gas emissions [49–52], air pollution [53,54], water use [55–58], land use [59,60], biodiversity loss [61,62] and materials use [63,64]. In this study, the input-output model is used to calculate the production-based carbon emissions from production based emission inventories for Chinese cities. The relationship between production- and consumption-based emissions is ‘consumption-based emissions = production-based emissions – emissions embodied in exports + emissions embodied in imports’.

The analytical framework of the input-output model was developed by Wassily Leontief in the late 1930s [65]. The basic linear equation of the input-output model is

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

where X is the total output vector whose element x_i is the output of sector i , Y is the final demand vector whose element y_i is the final demand of sector i , I is the identity matrix, and $(I - A)^{-1}$ is the Leontief inverse matrix.

To calculate consumption-based CO₂ emissions, we require the carbon intensity (i.e., CO₂ emissions per unit of economic output) for all economic sectors. Suppose k_i is the carbon intensity of sector i , then the consumption-based CO₂ emissions can be calculated as follows:

$$C = K(I - A)^{-1}Y^d \quad (2)$$

where C is a vector of total CO₂ emissions embodied in goods and services used for final demand, $K = [k_1 k_2 \dots k_n]$ is a vector of carbon intensity for all economic sectors, and $Y^d = \text{diag}(Y)$ means that the vector of Y is diagonalized [12,66].

Eq. (2) calculates the total emissions associated with the final demand, but it may not be able to distinguish CO₂ emissions from local production and imports. It is difficult to obtain details related to imports, so we use national data to calculate the emissions embodied in imports:

$$\bar{C} = \bar{K}(I - \bar{A})^{-1}\bar{Y}^d \quad (3)$$

where \bar{C} is the total embodied emissions in the import, \bar{K} is the vector of national carbon intensity, \bar{A} is the direct requirement matrix for the import, \bar{Y} is the import, and $\bar{Y}^d = \text{diag}(\bar{Y})$ means that the vector of \bar{Y} is diagonalized.

Notably, emissions from residential energy consumption are not included in our calculations.

2.2. Data sources

In this study, we use the input-output model to calculate consumption-based CO₂ emissions for thirteen cities in China. The input-output tables for the cities are derived from regional statistics bureaus. Population data are obtained from the database of the National Bureau of Statistics of China [4]. China does not officially release carbon emissions data, and data quality is relatively poor at the city level—with the exception of a few megacities. Therefore, we developed a method for constructing a production-based CO₂ emissions inventory for Chinese cities using the definition provided by the IPCC territorial emission accounting approach [67–69]. Each inventory covers 47 socioeconomic sectors, 20 energy types and 9 primary industry products.

3. Results

3.1. Consumption-based carbon emissions for thirteen cities in China

Table 1 shows the socio-economic information of the thirteen cities in 2007. It can be seen that Shanghai has the highest GDP per capita and the highest population density. On the contrary,

Hengshui has the lowest GDP per capita with only 12,724 Chinese Yuan (CNY) per capita. Capital formation occupies the highest percentage in the final demand. For example, Xian’s capital formation occupies more than 70% in the total final demand.

Consumption-based emissions include imported emissions (emissions embodied in imports) and domestic emissions (from the consumption of domestic products). Fig. 1 shows that imported emissions were much higher than domestic emissions in 2007 in most cities. In megacities such as Shanghai, Beijing and Tianjin, approximately 70% of consumption-based emissions are imported from other regions. Hengshui has the highest percentage of imported emissions in its total consumption-based emissions because its imports are approximately 11 times greater than its final consumption. Overall, this reveals that urban consumers rely largely on goods and services produced elsewhere in China. This result is consistent with studies on cities in other countries. For example, Hasegawa et al. [38] found that imported CO₂ emissions accounted for about 40–80% in total emissions for Japanese prefectures.

In several cities, including Chongqing, Shenyang and Harbin, more than half of the consumption-based CO₂ emissions occur within city boundaries. Approximately 29% of Harbin’s emissions are imported from other regions for two reasons. First, Harbin has lower imports than other cities. For example, Shijiazhuang’s imports are 4 times those of Harbin, although the two cities have similar GDPs. Second, the carbon intensity of Harbin’s exports is much higher than that of its imports. Specifically, the carbon intensity of its exports is 215 g CO₂ per CNY, which is 37% higher than that of its imports.

From the perspective of final consumption, CO₂ emissions are produced by four final demand categories, including household consumption, government, changes in inventories, and capital formation. Fig. 2 shows that capital formation is the largest contributor to consumption-based emissions, which corroborates previous research on CO₂ emissions in China [70–72]. The high contribution of capital investments to consumption-based emissions is driven by rapid urbanization, large-scale economic growth, and government policies [40,73]. Capital formation contributes more than 60% of emissions in four cities, including Shijiazhuang (65%), Ningbo (63%), Xian (61%) and Shenyang (61%). Shijiazhuang has the highest percentage of emissions derived from capital formation, which is determined by its consumption structure. Its capital formation accounted for 58% in its total final demands in 2007. After capital formation, household consumption is the second largest driver of emissions. The percentages of emissions produced by household consumption range between 19% (Ningbo) and 38% (Harbin). Harbin exhibits the highest percentage of emissions attributed to household consumption. In this city, capital formation and household consumption make similar contributions to final, with each contributing 38% of total CO₂ emissions.

Carbon emissions embodied in imports and exports vary greatly in the thirteen Chinese cities included in this study (see Fig. 3). Emissions embodied in imports for the four megacities are much larger than in other medium-sized cities. For example, emissions embodied in imports in Shanghai are 140 Mt CO₂, which is 13 times greater than in Hengshui. The sector of metal products is the largest contributor to the embodied emissions of imports. In the city of Dalian, the imports of metal products produce 10 Mt CO₂, which account for 26% of the total emissions embodied in imports. In addition, the sector of construction also cause substantial carbon emissions in Chinese cities. For example, Qingdao’s imports in Construction generate 11 Mt CO₂ or approximately 28% of total emissions embodied in imports.

For most cities, the emissions embodied in their imports are greater than the emissions embodied in their exports. For instance, the embodied emissions of Xian’s imports are 34 Gt CO₂, whereas

Table 1
Socio-economic information of the thirteen cities in 2007.

	Population (Million)	Area (km ²)	GDP per capita (¥ per person)	Household consumption (Million ¥)	Government consumption (Million ¥)	Fixed capital formation (Million ¥)	Inventory increase (Million ¥)	Export (Million ¥)	Import (Million ¥)
Beijing	12.2	16,411	78,762	284,654	221,379	408,256	47,571	1,179,544	1,183,462
Shanghai	13.8	6340	88,398	445,552	156,079	504,140	52,709	2,165,237	2,104,832
Tianjin	9.6	11,920	52,382	130,924	75,515	268,135	24,111	851,749	845,395
Chongqing	32.4	82,400	12,918	181,557	59,575	221,678	9046	245,238	299,169
Dalian	5.8	13,237	54,146	76,832	39,215	170,614	16,101	385,848	375,542
Harbin	9.9	53,840	24,680	69,486	41,707	105,799	19,634	111,420	104,367
Hengshui	4.3	8815	12,724	18,367	5798	20,927	7686	561,432	559,760
Ningbo	5.6	9816	60,844	66,565	40,943	166,523	27,301	710,087	667,917
Qingdao	7.6	11,282	49,955	100,176	41,389	172,300	19,382	571,674	526,269
Shenyang	7.1	12,948	45,383	79,783	50,200	181,827	2287	169,577	161,559
Shijiazhuang	9.6	15,848	24,841	67,565	26,044	128,040	113	527,903	512,420
Tangshan	7.2	13,472	38,355	71,417	25,075	69,382	33,204	337,393	258,530
Xian	7.6	10,108	23,065	70,717	27,502	126,904	16,928	102,712	168,490

Note: ¥ means Chinese Yuan (CNY).

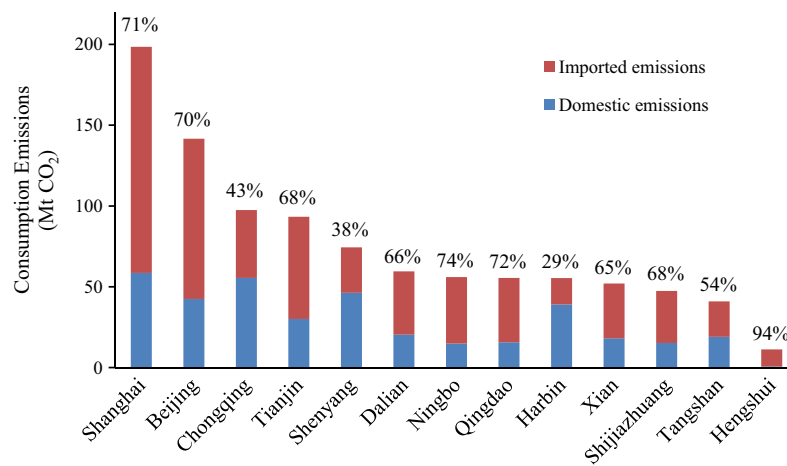


Fig. 1. Imported and domestic emissions in the total consumption-based CO₂ emissions. The percentages of imported emissions are shown above the bars.

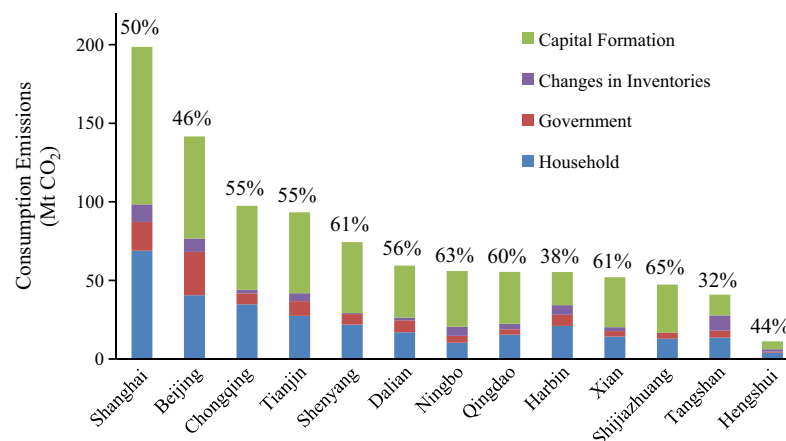


Fig. 2. Embodied CO₂ emissions in major final demand categories. The percentages of emissions induced by capital formation are shown above the bars.

the embodied emissions of its exports are only 6 Gt CO₂. In fact, Xian's imports were approximately 1.6 times greater than its exports in 2007. In addition, the carbon intensity of Xian's production is lower than that of its exports. The carbon intensity of Xian's imports was 201 g CO₂ per CNY in 2007, which was much higher than that of its exports (61 g CO₂ per CNY). Therefore, one unit of import embodies more CO₂ emissions than an equivalent unit of

export. However, the embodied emissions in imports are smaller than the embodied emissions in exports for five cities, including Tangshan, Shijiazhuang, Harbin, Ningbo and Shenyang. Therefore, the producer responsibility is greater than the consumer responsibility in these regions. For example, emissions embodied in Tangshan's imports equal 22 Gt CO₂, which is less than half the emissions embodied in its exports (55 Gt CO₂) mainly because

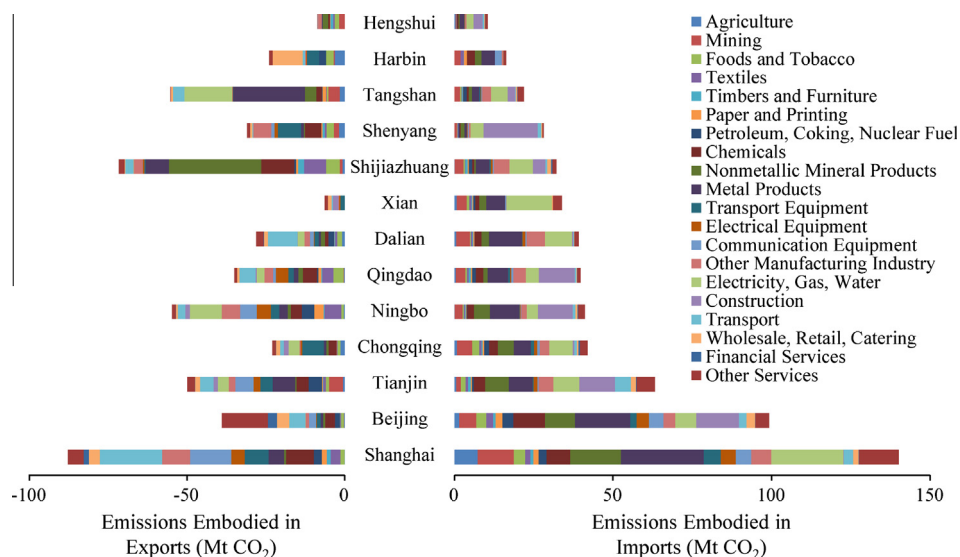


Fig. 3. CO₂ emissions embodied in imports and exports for thirteen cities.

the carbon intensity of its imports is much lower than that of its exports. The carbon intensities of Tangshan's imports and exports were 85 and 164 g CO₂ per CNY in 2007, respectively.

3.2. Comparisons between production- and consumption-based emissions

Fig. 4 compares production- and consumption-based carbon emissions in a selection of Chinese cities. It can be seen that there are great differences between production- and consumption-based emissions for all cities. It is mainly caused by two factors: trade deficit and different carbon intensity [74,75]. All thirteen cities are categorized by their trading patterns. Fig. 4 shows that five are production-based cities in which production-based emissions are higher than consumption-based emissions. Shijiazhuang is a typical production-based city with production- and consumption-based CO₂ emissions at 87 and 47 Mt, respectively. Its annual per capita production-based emissions total 9 tonnes, which is 83% higher than its annual per capita consumption-based emissions (5 tonnes). Notably, Shijiazhuang's imports and exports are almost equal, although there is a substantial difference between the CO₂ emissions embodied in its imports and exports, which is mainly due to its high-carbon-intensity domestic production. The average carbon intensity of its exports is 136 g CO₂ per CNY, which is much higher than that of its imports (63 g CO₂ per CNY). Therefore, improving technology and reducing carbon intensity are critical for these cities to control production-based emissions. Because of the large gap between the two approaches to emission accounting, the production-based cities prefer that consumption-based accounting be used to allocate responsibilities for climate change mitigation.

Consumption-based emissions are larger than production-based emissions in eight cities. For example, Xian's consumption-based CO₂ emissions are 52 Mt, which is more than twice its production-based emissions (24 Mt). In fact, Xian's imports are approximately 1.6 times more than its exports. In addition, the carbon intensity of Xian's domestic production is lower than other cities. The carbon intensity of its exports is 61 g CO₂ per CNY, which is similar to Tianjin. However, the carbon intensity of Xian's imports is 201 g CO₂ per CNY—much higher than its exports. Production-based accounting benefits these consumption-based cities in allocating responsibilities. Clearly, the most developed

cities in China, such as Beijing, Shanghai and Tianjin, tend to be consumption-based cities. On the contrary, most medium-sized cities are production-based cities. Production-based cities tend to become consumption-based cities as they undergo further socio-economic development.

Fig. 5, row 1, Left, shows the consumption-based emissions for thirteen cities in China. Overall consumption-based emissions are greatest in the four megacities, i.e., Shanghai (199 Mt CO₂), Beijing (142 Mt CO₂), Chongqing (97 Mt CO₂) and Tianjin (93 Mt CO₂). Consumption-based emissions in Shanghai are approximately 18 times those of Hengshui (11 Mt CO₂). Annual per capita consumption-based emissions in Shanghai, Beijing and Tianjin are 14, 12 and 10 tonnes of CO₂ per person, respectively (Fig. 5, row 1, Right). Some medium-sized cities, such as Shenyang, Dalian and Ningbo, have per capita emissions that are similar to Tianjin's. In Chongqing, per capita consumption-based emissions are very low (3 tonnes CO₂ per person), although this city's total consumption-based emissions are high.

With regard to production-based emissions, Shanghai is the largest emitter with 146 Mt CO₂ (Fig. 5, row 2, Left). Shijiazhuang has rather high production-based emissions (87 Mt CO₂), which are even higher than Beijing (81 Mt CO₂) and Tianjin (80 Mt CO₂). Domestic production-based emissions per unit of GDP reflect the technological level of a city's production (Fig. 5, row 2, Centre). Shijiazhuang has the highest carbon intensity of the thirteen Chinese cities, with 366 g CO₂ per CNY, which is one of the main reasons for its high production-based emissions. By contrast, Beijing and Shanghai have the highest levels of technology, and their carbon intensities are 85 and 120 g CO₂ per CNY, respectively. The highest annual per capita production-based emissions are found in Ningbo, Shenyang, Shanghai and Tangshan (10–12 tonnes CO₂ per person; Fig. 5, row 2, Right). In Chongqing, per capita production-based emissions are low, as are its per capita consumption-based emissions. We find a substantial difference between production- and consumption-based accounting in terms of overall carbon emissions as well as per capita levels. As a result, the choice of an emission accounting approach has a major impact on allocating responsibilities for climate change mitigation. Thus, the two different accounting approaches must be considered comprehensively in identifying fair mitigation policies.

Overall emissions embodied in imports are shown in Fig. 5, row 3, Left. We find that more developed cities tend to import more CO₂

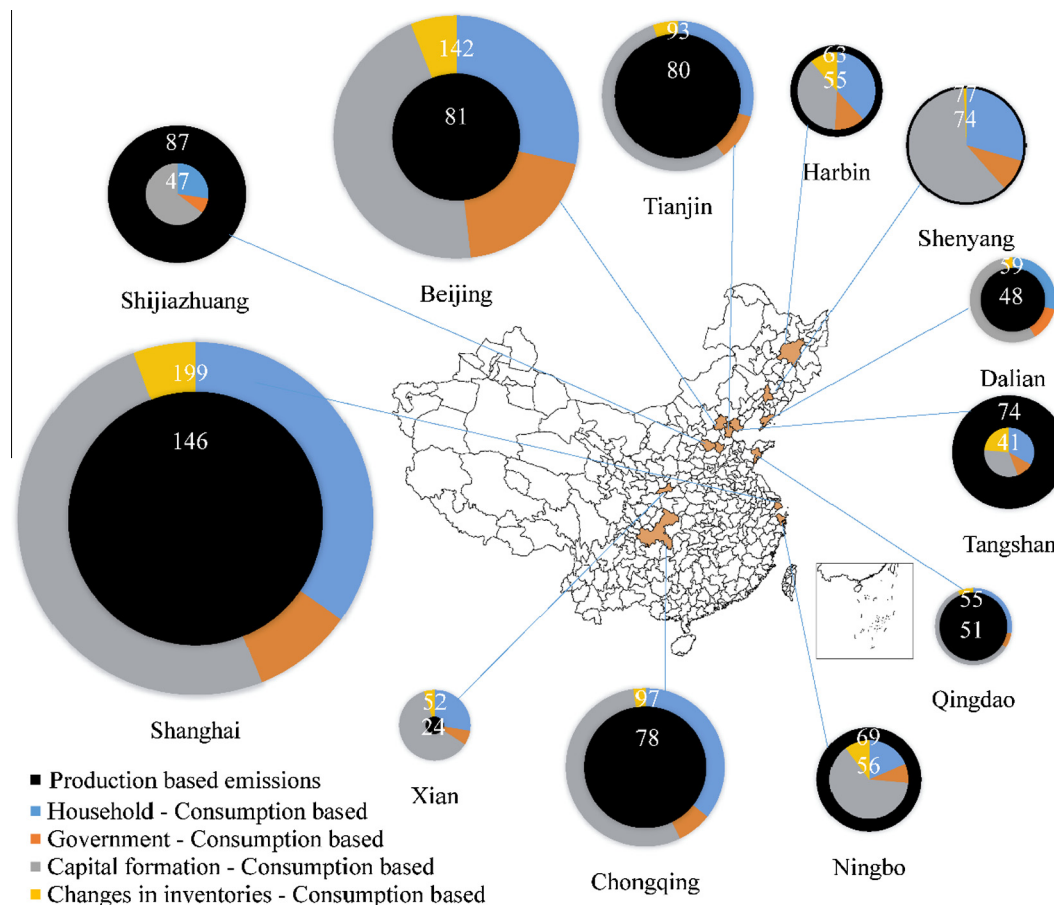


Fig. 4. Production- and consumption-based CO₂ emissions at the city level. The black circles represent production-based emissions, whereas the other circles represent consumption-based emissions, with the four colours representing emissions produced by household consumption, government, capital formation and changes in inventory, respectively. Total production- and consumption-based CO₂ emissions are shown in the pie charts (in Mt CO₂). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

emissions. As the two most developed cities in China, Shanghai and Beijing have the largest amounts of emissions embodied in imports. By contrast, Harbin and Hengshui, two less developed cities, have the lowest amounts of emissions embodied in imports, which further confirms that production-based cities tend to become consumption-based cities as they undergo further socio-economic development. In the case of exports (Fig. 5, row 4, Left), emissions embodied in exports are greatest in Shanghai (88 Mt CO₂) and Shijiazhuang (72 Mt CO₂), which is a primary reason for Shijiazhuang's high production-based CO₂ emissions.

4. Conclusions

Consumption-based CO₂ emissions have been accepted by an increasing number of researchers and policy makers. In this study, we calculate consumption-based CO₂ emissions for thirteen Chinese cities and find that consumption in these cities not only leads to carbon emissions within their own boundaries but also induces emissions in other regions via interregional trade. For instance, more than 70% of consumption-based emissions in Beijing and Shanghai are imported from other regions, which shows that urban consumers rely largely on goods and services imported from elsewhere in China. Therefore, cooperation between consuming and producing regions is critical to mitigate climate change. China currently has pilot carbon trading systems in seven cities and plans to establish a national emissions trading scheme by 2017, which will help improve regional cooperation on mitigation in China. In addition,

a clean development mechanism (CDM) within China may encourage cooperation between cities and their neighbours. Under such a mechanism, cities may invest in their surrounding areas and obtain carbon emission permits.

Capital formation is the largest contributor to consumption-based emissions in the thirteen cities. For example, more than 60% of consumption-based emissions were caused by capital formation in Shenyang and Ningbo in 2007. The high contribution of capital investment to consumption-based emissions is driven by rapid urbanization, large-scale economic growth, and government policies. Household consumption is the second largest driver of emissions, but the percentage of emissions induced by household consumption remains much smaller in China than in other countries. In the future, more residents will transition from rural to urban lifestyles as China continues its rapid urbanization, leading to increased CO₂ emissions related to household consumption.

All thirteen cities are categorized in terms of their trading patterns. In five production-based cities, production-based emissions are higher than consumption-based emissions. Shijiazhuang is a typical production-based city, whose production- and consumption-based CO₂ emissions are 87 and 47 Mt, respectively. Improving technology and reducing carbon intensity are critical if these cities are to control production-based emissions. Conversely, eight of the cities are consumption-based cities in which consumption-based emissions exceed production-based emissions. For example, Xian's consumption-based CO₂ emissions are 52 Mt, more than twice its production-based emissions (24 Mt).

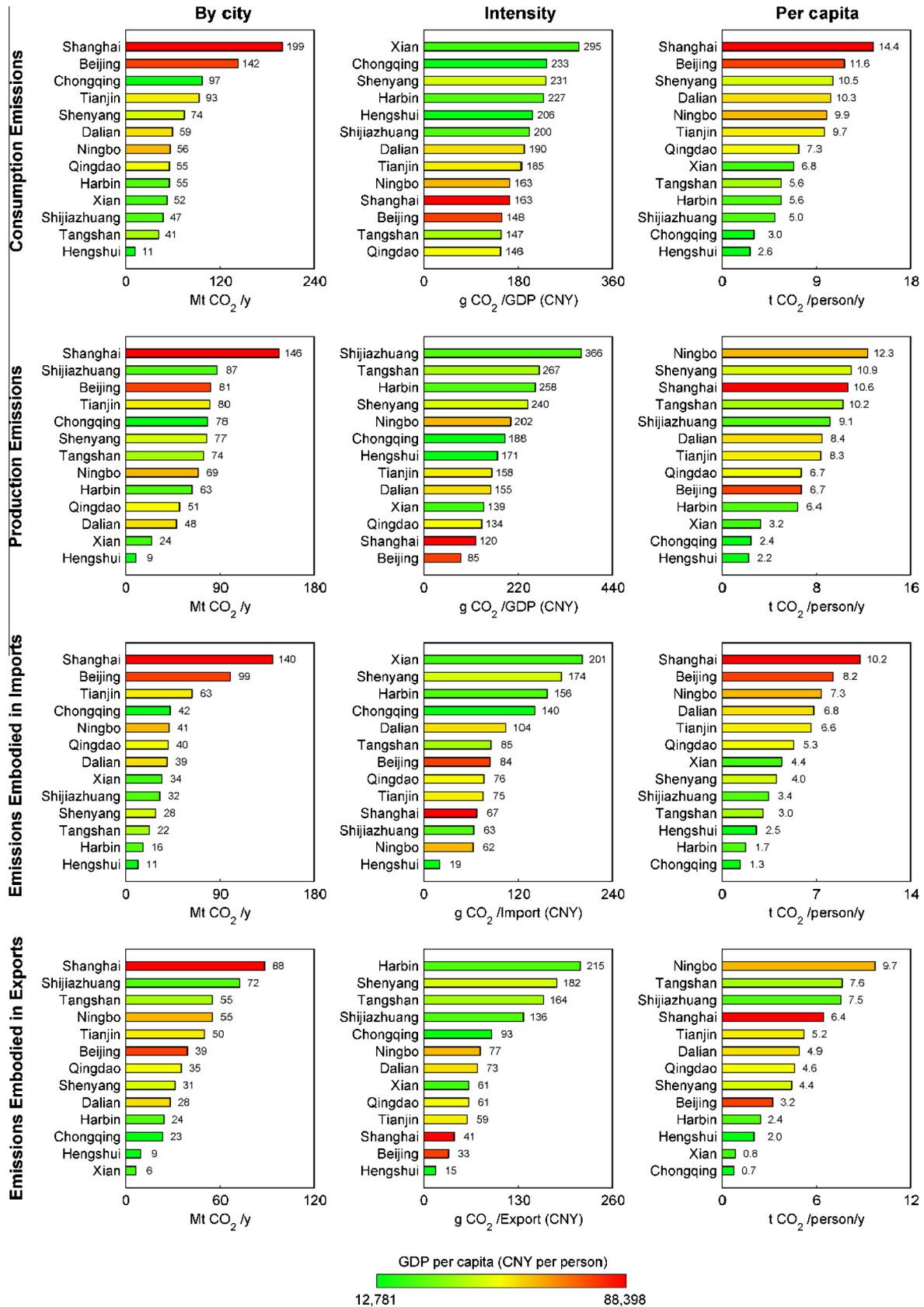


Fig. 5. Thirteen cities' consumption-based emissions (row 1), production-based emissions (row 2), emissions embodied in imports (row 3), and emissions embodied in exports (row 4). This figure shows regional emissions totals (left column), emissions intensity (centre column), and per capita emissions (right column). The colour of the bars corresponds to the city's GDP per capita, from the most affluent cities in red to the least developed cities in green (see scale). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Clearly, the most developed cities in China tend to be consumption-based cities, such as Beijing, Shanghai and Tianjin. Similarly, most medium-sized cities are production-based cities, and production-based cities tend to become consumption-based cities as they undergo further socioeconomic development. Based on this trend, more Chinese cities will transition from production-based to consumption-based cities as a result of rapid social development. Consequently, more production-based CO₂ emissions will be transferred to rural areas or abroad. Therefore, rural and urban areas must cooperate to tackle the challenge of climate change within China.

At present, few governments choose consumption-based accounting in determining their mitigation policies, and most global climate change agreements are based on production-based accounting, including the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. Consumption-based accounting's advantages have been shown in many studies; this approach elucidates the drivers of emissions growth, improves cost-effectiveness and justice, addresses carbon leakage, promotes environmental comparative advantages, and encourages technology diffusion [13,22,26,40]. There are substantial differences between production- and consumption-based accounting in terms of calculating both overall and per capita carbon emissions levels. As a result, the selection of an emission accounting approach has a major influence on the allocation of responsibilities for climate change mitigation. The two different accounting approaches must thus be considered comprehensively to identify fair mitigation policies. At the city level, consumption-based accounting can help cities to reduce emissions both within city boundaries and along their entire supply chains at minimum cost. Interregional cooperation on climate change mitigation should employ consumption-based accounting to allocate mitigation responsibilities more fairly and efficiently. Therefore, consumption-based carbon emission accounting is a complementary tool for promoting climate action at the city level.

Acknowledgements

This study was supported by the Natural Science Foundation of China (41328008), the UK Economic and Social Research Council (ES/L016028/1) Natural Environment Research Council (NE/N00714X/1) and British Academy Grant (AF150310).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.apenergy.2016.06.094>.

References

- [1] Chang K, Chang H. Cutting CO₂ intensity targets of interprovincial emissions trading in China. *Appl Energy* 2016;163:211–21.
- [2] Arce G, López LA, Guan D. Carbon emissions embodied in international trade: the post-China era. *Appl Energy*; 2016. <http://dx.doi.org/10.1016/j.apenergy.2016.05.084>.
- [3] Xinhua. Enhanced actions on climate change: China's intended nationally determined contributions; 2015. <http://news.xinhuanet.com/english/china/2015-06/30/c_134369837.htm> [accessed 2015-09-01].
- [4] NBSC. National data; 2015. <<http://data.stats.gov.cn/english/>> [accessed 2015-02-01].
- [5] Wei Y, Liu L, Wu G, Zou L. *Energy economics: CO₂ emissions in China*. New York: Springer; 2011.
- [6] Nam K-M, Waugh CJ, Paltsev S, Reilly JM, Karplus VJ. Carbon co-benefits of tighter SO₂ and NO_x regulations in China. *Glob Environ Change* 2013;23:1648–61.
- [7] Dhakal S. GHG emissions from urbanization and opportunities for urban carbon mitigation. *Curr Opin Environ Sustain* 2010;2:277–83.
- [8] Dhakal S. Urban energy use and carbon emissions from cities in China and policy implications. *Energy Policy* 2009;37:4208–19.
- [9] Senbel M, McDaniels T, Dowlatabadi H. The ecological footprint: a non-monetary metric of human consumption applied to North America. *Glob Environ Change* 2003;13:83–100.
- [10] Shiget S, Yamagata Y, Li R, Hidaka M, Horio M. An easily traceable scenario for 80% CO₂ emission reduction in Japan through the final consumption-based CO₂ emission approach: a case study of Kyoto-city. *Appl Energy* 2012;90:201–5.
- [11] Zhang B, Qiao H, Chen ZM, Chen B. Growth in embodied energy transfers via China's domestic trade: evidence from multi-regional input–output analysis. *Appl Energy*; 2015. <http://dx.doi.org/10.1016/j.apenergy.2015.09.076>.
- [12] Peters GP. From production-based to consumption-based national emission inventories. *Ecol Econ* 2008;65:13–23.
- [13] 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. *Glob Environ Change* 2014;24:75–87.
- [14] Atkinson G, Hamilton K, Ruta G, Van Der Mensbrugge D. Trade in 'virtual carbon': empirical results and implications for policy. *Glob Environ Change* 2011;21:563–74.
- [15] Wiedmann T. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecol Econ* 2009;69:211–22.
- [16] Peters GP, Hertwich EG. Post-Kyoto greenhouse gas inventories: production versus consumption. *Clim Change* 2008;86:51–66.
- [17] Jakob M, Steckel JC, Edenhofer O. Consumption- versus production-based emission policies. *Annu Rev Resour Econ* 2014;6:297–318.
- [18] Girod B, van Vuuren DP, Hertwich EG. Climate policy through changing consumption choices: options and obstacles for reducing greenhouse gas emissions. *Glob Environ Change* 2014;25:5–15.
- [19] Steininger KW, Lininger C, Meyer LH, Munoz P, Schinko T. Multiple carbon accounting to support just and effective climate policies. *Nat Clim Change*; 2015. <http://dx.doi.org/10.1038/nclimate2867>.
- [20] Guan D, Lin J, Davis SJ, Pan D, He K, Wang C, et al. Reply to Lopez et al.: consumption-based accounting helps mitigate global air pollution. *Proc Natl Acad Sci USA* 2014;111:E2631.
- [21] Larsen HN, Hertwich EG. The case for consumption-based accounting of greenhouse gas emissions to promote local climate action. *Environ Sci Policy* 2009;12:791–8.
- [22] Peters GP, Hertwich EG. CO₂ embodied in international trade with implications for global climate policy. *Environ Sci Technol* 2008;42:1401–7.
- [23] 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. *Appl Energy* 2014;123:19–28.
- [24] Hertwich EG, Peters GP. Carbon footprint of nations: a global, trade-linked analysis. *Environ Sci Technol* 2009;43:6414–20.
- [25] Davis SJ, Caldeira K. Consumption-based accounting of CO₂ emissions. *Proc Natl Acad Sci USA* 2010;107:5687–92.
- [26] Peters GP, Minx JC, Weber CL, Edenhofer O. Growth in emission transfers via international trade from 1990 to 2008. *Proc Natl Acad Sci USA* 2011;108:8903–8.
- [27] Wood R, Dey CJ. Australia's carbon footprint. *Econ Syst Res* 2009;21:243–66.
- [28] 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. *Econ Syst Res* 2009;21:267–90.
- [29] 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. *Econ Syst Res* 2010;22:19–42.
- [30] Barrett J, Peters G, Wiedmann T, Scott K, Lenzen M, Roelich K, et al. Consumption-based GHG emission accounting: a UK case study. *Clim Policy* 2013;13:451–70.
- [31] Feng K, Davis SJ, Sun L, Li X, Guan D, Liu W, et al. Outsourcing CO₂ within China. *Proc Natl Acad Sci USA* 2013;110:11654–9.
- [32] Hoornweg D, Sugar L, Gomez CLT. Cities and greenhouse gas emissions: moving forward. *Environ Urban* 2011;1:1–21.
- [33] Sugar L, Kennedy C, Leman E. Greenhouse gas emissions from Chinese cities. *J Ind Ecol* 2012;16:552–63.
- [34] 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 cities: the case of Beijing, Tianjin, Shanghai and Chongqing. *Energy* 2012;37:245–54.
- [35] Creutzig F, Baiocchi G, Bierkandt R, Pichler P-P, Seto KC. Global typology of urban energy use and potentials for an urbanization mitigation wedge. *Proc Natl Acad Sci USA* 2015;112:6283–8.
- [36] Jan M, Giovanni B, Thomas W, John B, Felix C, Kuishuang F, et al. Carbon footprints of cities and other human settlements in the UK. *Environ Res Lett* 2013;8:035039.
- [37] Fan J, Guo X, Marinova D, Wu Y, Zhao D. Embedded carbon footprint of Chinese urban households: structure and changes. *J Clean Prod* 2012;33:50–9.
- [38] Hasegawa R, Kagawa S, Tsukui M. Carbon footprint analysis through constructing a multi-region input–output table: a case study of Japan. *J Econ Struct* 2015;4:1–20.
- [39] Dhakal S. Urban energy use and greenhouse gas emissions in Asian megacities. Kitakyushu, Japan: Institute for Global Environmental Strategies; 2004.
- [40] Feng K, Hubacek K, Sun L, Liu Z. Consumption-based CO₂ accounting of China's megacities: the case of Beijing, Tianjin, Shanghai and Chongqing. *Ecol Indic* 2014;47:26–31.
- [41] Wiedmann T. A first empirical comparison of energy footprints embodied in trade—MRIO versus PLUM. *Ecol Econ* 2009;68:1975–90.

- [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. *Econ Syst Res* 2009;21:187–216.
- [43] Wiedmann T. Carbon footprint and input-output analysis – an introduction. *Econ Syst Res* 2009;21:175–86.
- [44] Dietzenbacher E, Lenzen M, Los B, Guan D, Lahr ML, Sancho F, et al. Input-output analysis: the next 25 years. *Econ Syst Res* 2013;25:369–89.
- [45] Wiedmann T, Lenzen M, Turner K, Barrett J. Examining the global environmental impact of regional consumption activities—Part 2: review of input–output models for the assessment of environmental impacts embodied in trade. *Ecol Econ* 2007;61:15–26.
- [46] 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.
- [47] 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 Build* 2013;62:97–106.
- [48] 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.
- [49] Yan J, Zhao T, Kang J. Sensitivity analysis of technology and supply change for CO₂ emission intensity of energy-intensive industries based on input–output model. *Appl Energy* 2016;171:456–67.
- [50] Su B, Ang BW. Input–output analysis of CO₂ emissions embodied in trade: a multi-region model for China. *Appl Energy* 2014;114:377–84.
- [51] Mi Z-F, Pan S-Y, Yu H, Wei Y-M. Potential impacts of industrial structure on energy consumption and CO₂ emission: a case study of Beijing. *J Clean Prod* 2015;103:455–62.
- [52] Wei Y-M, Mi Z-F, Zhang H. Progress of integrated assessment models for climate policy. *Syst Eng Theory Pract* 2013;33:1905–15 [in Chinese].
- [53] 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. *Proc Natl Acad Sci USA* 2014;111:1736–41.
- [54] Yang S, Fath B, Chen B. Ecological network analysis of embodied particulate matter 2.5 – a case study of Beijing. *Appl Energy*; 2016. <http://dx.doi.org/10.1016/j.apenergy.2016.04.087>.
- [55] Cazarro I, Duarte R, Sánchez Chóliz J. Multiregional input–output model for the evaluation of Spanish water flows. *Environ Sci Technol* 2013;47:12275–83.
- [56] Aviso KB, Tan RR, Culaba AB, Cruz Jr JB. Fuzzy input–output model for optimizing eco-industrial supply chains under water footprint constraints. *J Clean Prod* 2011;19:187–96.
- [57] Ewing BR, Hawkins TR, Wiedmann TO, Galli A, Ertug Arcin A, Weinzettel J, et al. Integrating ecological and water footprint accounting in a multi-regional input–output framework. *Ecol Indic* 2012;23:1–8.
- [58] Yu Y, Hubacek K, Feng K, Guan D. Assessing regional and global water footprints for the UK. *Ecol Econ* 2010;69:1140–7.
- [59] Costello C, Griffin WM, Matthews HS, Weber CL. Inventory development and input–output model of US land use: relating land in production to consumption. *Environ Sci Technol* 2011;45:4937–43.
- [60] Weinzettel J, Hertwich EG, Peters GP, Steen-Olsen K, Galli A. Affluence drives the global displacement of land use. *Glob Environ Change* 2013;23:433–8.
- [61] Lenzen M, Moran D, Kanemoto K, Foran B, Lobefaro L, Geschke A. International trade drives biodiversity threats in developing nations. *Nature* 2012;486:109–12.
- [62] Lenzen M, Murray SA. A modified ecological footprint method and its application to Australia. *Ecol Econ* 2001;37:229–55.
- [63] Weisz H, Duchin F. Physical and monetary input–output analysis: What makes the difference? *Ecol Econ* 2006;57:534–41.
- [64] Wiedmann TO, Schandl H, Lenzen M, Moran D, Suh S, West J, et al. The material footprint of nations. *Proc Natl Acad Sci USA* 2015;112:6271–6.
- [65] Leontief WW. Quantitative input and output relations in the economic systems of the United States. *Rev Econ Stat* 1936;18:105–25.
- [66] Turner K, Lenzen M, Wiedmann T, Barrett J. Examining the global environmental impact of regional consumption activities—Part 1: a technical note on combining input–output and ecological footprint analysis. *Ecol Econ* 2007;62:37–44.
- [67] 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. *Mitig Adapt Strateg Glob Chang*; 2015. <http://dx.doi.org/10.1007/s11027-015-9660-1>.
- [68] Shan Y, Guan D, Liu J, Liu Z, Liu J, Schroeder H, et al. CO₂ emissions inventory of Chinese cities. *Atmos Chem Phys Discuss*; 2016. <http://dx.doi.org/10.5194/acp-2016-176>.
- [69] Shan Y, Liu J, Liu Z, Xu X, Shao S, Wang P, et al. New provincial CO₂ emission inventories in China based on apparent energy consumption data and updated emission factors. *Appl Energy*; 2016. <http://dx.doi.org/10.1016/j.apenergy.2016.03.073>.
- [70] Feng K, Siu YL, Guan D, Hubacek K. Analyzing drivers of regional carbon dioxide emissions for China. *J Ind Ecol* 2012;16:600–11.
- [71] Guan D, Peters GP, Weber CL, Hubacek K. Journey to world top emitter: an analysis of the driving forces of China's recent CO₂ emissions surge. *Geophys Res Lett* 2009;36:1–5.
- [72] Peters GP, Weber CL, Guan D, Hubacek K. China's growing CO₂ emissions: a race between increasing consumption and efficiency gains. *Environ Sci Technol* 2007;41:5939–44.
- [73] Minx JC, Giovanni B, Peters GP, Weber CL, Dabo G, Klaus H. A “carbonizing dragon”: China's fast growing CO₂ emissions revisited. *Environ Sci Technol* 2011;45:9144–53.
- [74] Jakob M, Marschinski R. Interpreting trade-related CO₂ emission transfers. *Nat Clim Change* 2013;3:19–23.
- [75] 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. *Environ Sci Technol* 2014;48:36–44.