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Consumption-based CO_2 accounting of China's megacities: The case of Beijing, Tianjin, Shanghai and Chongqing

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ABSTRACT

China has experienced rapid urbanization in the last three decades, with more than half of the population living in cities since 2012. The extent of urban production and urban lifestyles has become one of the main drivers for China's CO_2 emissions. To analyze drivers of CO_2 emissions we use a consumption-based accounting approach that allocates all emissions along the production chain to the product and place of final consumption, whereas a production-based approach would allocate all emissions to the place of origin. In this study, we focus on the spatial distribution of production activities leading to CO_2 emissions across China as a consequence of final consumption in four Chinese mega cities: Beijing, Shanghai, Tianjin, and Chongqing. Urban consumption not only causes a large amount of emissions within its territory, but also imposes even much more emissions to its surrounding provinces via interregional supply chains. Results show that more than 48% of CO_2 emissions related to goods consumed in Chongqing and more than 70% for Beijing, Shanghai and Tianjin occurred outside of the respective city boundary. In addition to the usual focus on efficiency, our analysis adds insights into the causes of CO_2 emissions by looking at the drivers and types of consumption. Addressing consumption patterns in China's cities is critical for China's low carbon development.

1. Introduction

Fast economic growth and large scale urbanization have led China to be the world top CO_2 emitter (Feng et al., 2012; Guan et al., 2009; Liu et al., 2012c). In the past three decades, China's urban population has rapidly increased to more than 700 million from less than 200 million. At present, more than half of China's population live in urban areas (NSBC, 2013). Large scale urbanization in China has led to unprecedented urban expansion and infrastructure development, which requires significant product, materials and other natural resource inputs and results in huge waste streams and emissions such as CO_2 emissions. At the same time, migration from rural to urban has led to higher incomes and thus a substantial increase in household consumption and more carbon intensive lifestyles (Feng et al., 2009; Guan et al., 2009; Hubacek et al., 2009, 2007).

It is now commonly accepted that accounts of territorial GHG emissions, i.e. those occurring within jurisdictional boundaries, are necessary and useful but insufficient for depicting the true contributions of human settlements to global warming. This is because urban economies inevitably draw on resources from places outside their geographical boundaries, causing emissions elsewhere (Hubacek et al., 2014; Lenzen and Peters, 2010). There are numerous studies on consumption-based CO_2 emissions at the national and global levels (e.g. Davis and Caldeira, 2010; Hertwich and Peters, 2009; Minx et al., 2008; Wiedmann and Barrett, 2011; Wilting and Vringer, 2009; Wood and Dey, 2009); in contrast, only few studies calculated consumption-based emissions at the city level (e.g. Hubacek et al., 2009; Larsen and Hertwich, 2010; Lenzen and Peters, 2010; Minx et al., 2013).

In China, climate change has received considerable attention after the 2009 United Nations Climate Change Conference in Copenhagen. At the conference China committed to reducing the carbon intensity of its economy (i.e. CO_2 emissions per unit of GDP) by 40–45% from 2005 levels and to generating 15% of its primary energy from non-fossil sources by 2020 (Su, 2010). However, China is facing tough challenges to balance economic growth and slow

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down the growth of CO_2 emissions. The continuing fast pace of urbanization will most likely cause more emissions owing to the increase of household consumption and expansion of urban infrastructure. With the increasing inter-regional trade, goods and services consumed in one place are often produced in other places. Thus, there is an urgent need of cooperation between the consuming and producing regions to tackle the emissions challenge within China. In this study, we analyze the spatial distribution of CO_2 emissions across China triggered by urban consumption in the top-four major cities: Beijing, Shanghai, Tianjin, and Chongqing.

2. Materials and methods

2.1. Multi-regional input–output model

Multiregional input–output (MRIO) analysis is a popular tool which enables analysts to explore the entire supply chain and the associated ('embodied') emissions from each upstream stage of the supply chain of a commodity (Wiedmann, 2009). At its core is an accounting procedure relying on regional economic input–output (I–O) tables and inter-regional trade matrices, depicting the flows of money to and from each sector within and between the interlinked economies, and thus revealing each sector's entire supply chain. This method has been applied to studies dealing with a wide-range of environmental issues such as land use (e.g. Hubacek and Sun, 2001; Weinzettel et al., 2013; Yu et al., 2013a, 2013b), water consumption (e.g. Cazcarro et al., 2013; Ewing et al., 2012; Feng et al., 2011a, 2011b; Lenzen, 2009; Yu et al., 2010), energy consumption and CO_2 emissions (e.g. Barrett et al., 2013; Davis et al., 2011; Feng et al., 2013; Larsen and Hertwich, 2009; Liang et al., 2007; Meng et al., 2013; Peters et al., 2011; Steen-Olsen et al., 2012), materials use (e.g. Wiedmann et al., 2013), and biodiversity loss (e.g. Lenzen et al., 2012).

A MRIO table is a collection of regional transaction tables, T^*, which connects supplying industries in region r with using industries in region s. As presented in Table 1, T^* consists of diagonal inter-industry blocks (i.e. T^{rr} and T^{ss}, intraregional transactions), and off-diagonal blocks (i.e. T^{rs} and T^{sr}, interregional transactions), intraregional (y^{rr} and y^{ss}) and interregional find demand (y^{rs} and y^{sr}), value added (v^r and v^s), international import to processing industries (m^r and m^s) and find demand sectors (m^{yr} and m^{ys}), and international exports of producing sectors (e^r and e^s) (see Table 1).

In a MRIO framework, different regions are connected through inter-regional trade, T^{rs} and T^{sr}. The technical coefficient sub-matrix A^{rs} consists of $\{a_{ij}^{rs}\}$ is given by $a_{ij}^{rs} = T_{ij}^{rs}/x_j^s$, in which T_{ij}^{rs} is the inter-sector monetary flow from sector i in region r to sector j in region s; x_j^s is the total output of sector j in region s. The final demand matrix is $\{y_i^{rs}\}$, where y_i^{rs} is the final demand of region s for goods of sector i from region r. Using matrix notation and dropping the subscripts, we have

$$A = \begin{bmatrix} A^{11} & A^{12} & \cdots & A^{1n} \\ A^{21} & A^{22} & \cdots & A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & \cdots & A^{nn} \end{bmatrix}; \quad Y = \begin{bmatrix} y^{11} & y^{12} & \cdots & y^{1n} \\ y^{21} & y^{22} & \cdots & y^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y^{n1} & y^{n2} & \cdots & y^{nn} \end{bmatrix}; \quad x = \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix}$$

Consequently, the MRIO framework can be written as:

$$x = Ax + y \tag{1}$$

By solving x, we have

$$x = (I - A)^{-1} y \tag{2}$$

where $(I - A)^{-1}$ is the Leontief inverse matrix which captures both direct and direct economic inputs to satisfy one unit of final demand in monetary value; I is the identity matrix with ones on the diagonal and zeros on the off-diagonal.

To calculate the consumption based CO_2 emissions, we extend the MRIO table with a vector of sectoral CO_2 emission coefficients for all regions, k:

$$k = \begin{bmatrix} k_1 & k_2 & \cdots & k_n \end{bmatrix}$$

Thus, the total consumption-based CO_2 emissions for all regions can be calculated by:

$$CO_2 = k(I - A)^{-1} y \tag{3}$$

where CO_2 is a vector of the total CO_2 emissions embodied in goods and services used for the final demand of all regions; k is a vector of CO_2 emissions per unit of economic output for all economic sectors in all regions.

While Eq. (3) captures well the total direct and indirect emissions associated with the final demand of a region, it may not be able to distinguish the emissions from domestic production and import. To calculate the emissions embodied in import of region s, we modify Eq. (3) to:

$$CO_2^{imp} = \tilde{k}(I - A)^{-1} y^s \tag{4}$$

where CO_2^{imp} is the total embodied emissions in import of region s; $\tilde{k}$ is a vector of sectoral CO_2 emission coefficients with zeros for the sectoral emission coefficients of region s; $y^{\cdot s}$ is the final demand vector of region s.

It is important to note that the scope of this study is the emissions produced within China, thus emissions from abroad are not included in our calculations.

2.2. Data sources

In this study, we use a MRIO table for China consisting of 30 regions with 30 sectors in each region. The Chinese 2007 MRIO table was constructed and compiled by Liu and his colleagues (Liu et al., 2012a). China does not officially publish annual CO_2 emissions data. Therefore, in this study we estimate CO_2 emissions of the 30 provinces based on China's provincial energy statistics. To convert energy consumption to CO_2 emissions, we adopt the IPCC reference approach (IPCC, 2006) as described by Peters et al. (2007) and applied in previous work on China (Feng et al., 2013, 2012; Guan et al., 2008, 2009). However, China's specific emission factors are used instead of IPCC default value, in order to avoid an over estimation of China's emissions. Detailed emission calculation processes were introduced in previous studies (Feng et al., 2013; Liu et al., 2012b). We apply the method to calculate emissions for all provinces in 2007. The inventories include emissions from

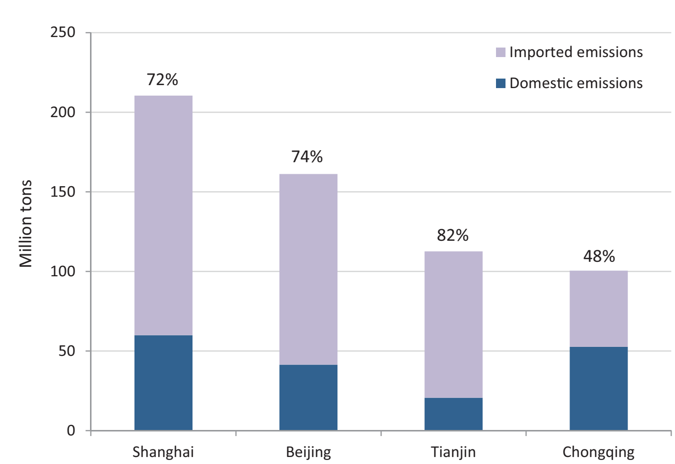

Fig. 1. Domestic and imported CO_2 emissions in the carbon footprint of the four megacities (in million tons). The percentages of emissions embedded in import for the four megacities are shown on the top of the bars.

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Table 1
A two regions multiregional input–output table.

	Intermediate demand		Final demand		International exports	Gross output
	Region *r*	Region *s*	Region *r*	Region *s*		
Intermediate input						
Region *r*	T^{rr}	T^{rs}	y^{rr}	y^{rs}	e^r	x^r
Region *s*	T^{sr}	T^{ss}	y^{sr}	y^{ss}	e^s	x^s
Value added	v^r	v^s				
International imports	m^r	m^s	m^{yr}	m^{ys}		
Gross input	x^r	x^s				

fuel combustion and cement production. Total energy consumption by production sectors and residents provide the basis for calculating CO_2 emissions from energy combustion. Provincial energy consumption data was collected from the Provincial Statistical Yearbooks. Provincial energy balance sheets were collected from the China Energy Statistical Yearbook 2008. From the Provincial Statistical Yearbooks and the China Statistical Yearbook, eighteen types of fuels are used in this study, namely raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquid petroleum gas, refinery gas, other petroleum products, natural gas, and other energy.

3. Results

A few studies have shown that many social and economic factors, such as per capita GDP, population density, and education, may drive local consumption-based emissions and found that consumption-based CO_2 emissions increase with growth of income, education, and car ownership, while population density may drive the emission down but the impact remains limited (Baiocchi et al., 2010; Minx et al., 2013). Table 2 shows the socio-economic information and CO_2 emissions of the four megacities in 2007. From the table we can see that Shanghai has the highest population density, the highest per capita GDP and at the same time the highest consumption-based CO_2 emissions per person compared with the other three cities. Per capita territorial emissions in Beijing are much lower than the emissions in Tianjin, but per capita consumption-based emissions are almost equal in these two cities due to the higher per capita GDP in Beijing. Chongqing is less developed than the other three cities and its per capita consumption-based emissions are less than half of the emissions of the other three cities.

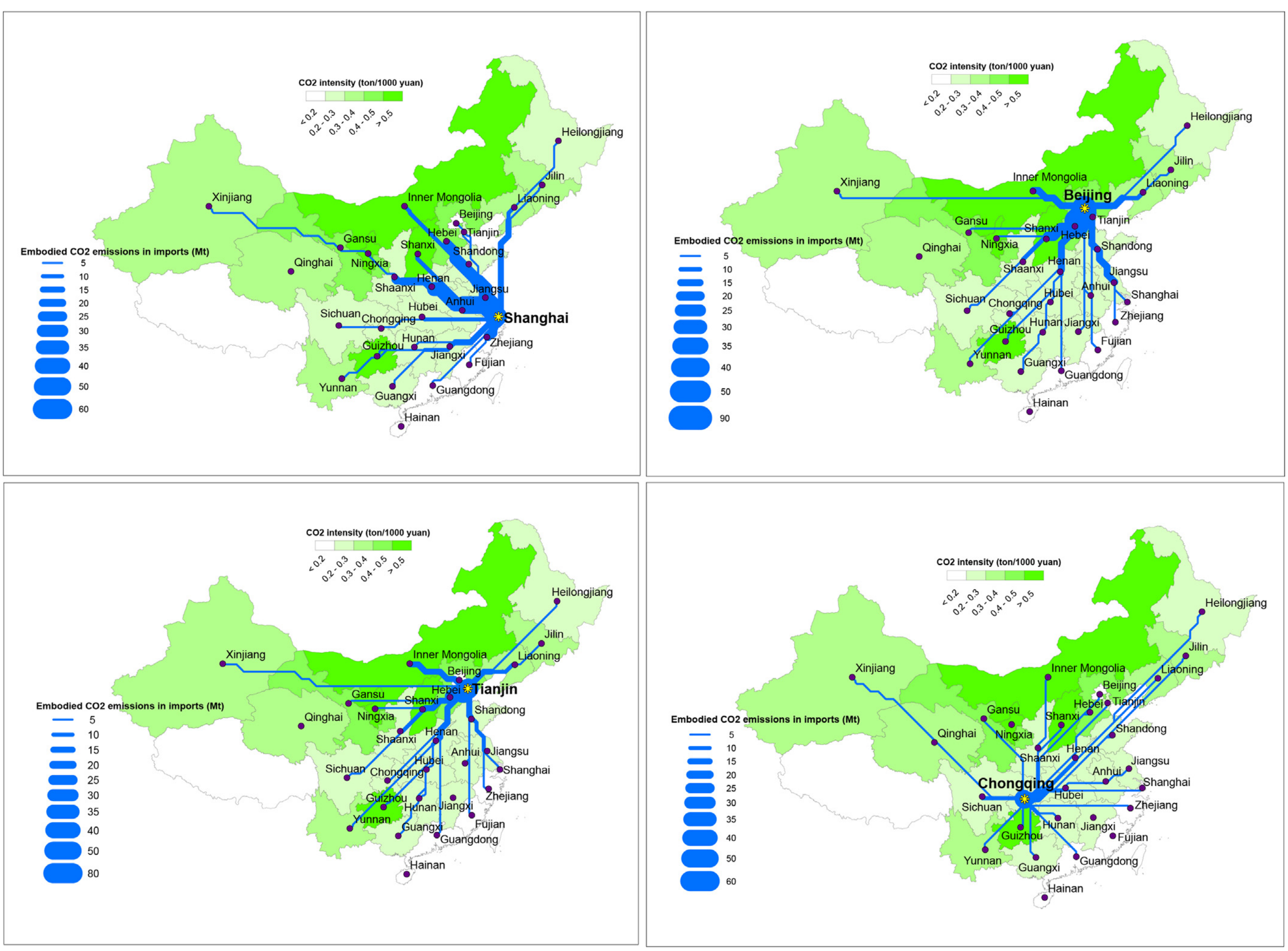

Fig. 2. Spatial distribution of CO_2 emissions across China as triggered by final consumption in the four Chinese megacities (in million tons).

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Table 2
Socio-economic information and CO_2 emissions of the four megacities in 2007.

	Shanghai	Beijing	Tianjin	Chongqing
Population (million)	19	16	11	28
Area (km^2)	6219	16,411	11,920	82,400
Population density (person/km^2)	2988	995	935	342
GDP/capita (RMB)	65,347	56,044	45,829	14,622
Territory CO_2 emissions (million tons)	200	109	108	92
Territory CO_2 emissions per person (ton)	10.8	6.7	9.7	3.3
Consumption-based CO_2 emissions (million tons)	209	161	112	100
Consumption-based CO_2 emissions per person (ton)	11.3	9.8	10.0	3.6

Data sources: Beijing, Tianjin, Shanghai, and Chongqing Statistical Yearbooks 2008.

Fig. 1 shows that in 2007 more than 48% of CO_2 emissions related to goods consumed in Chongqing and more than 70% for Beijing, Shanghai and Tianjin occurred outside of the respective city boundary. Overall, it confirms that urban consumers in China are largely relying on goods produced elsewhere, thus imposing emissions to other regions.

Fig. 2 shows the spatial distribution of the CO_2 emissions across Chinese regions which are triggered by consumption in the four megacities. From the figure we can see that consumption in Beijing heavily relies on production in its surrounding region, Hebei. In fact, 22% of the CO_2 emissions associated with goods consumed in Beijing were imported from Hebei in 2007. In addition, Beijing outsourced 7%, 6% and 4% of its consumption-based emissions to Inner Mongolia, Shanxi, and Shandong. Compared with Beijing, Tianjin mainly outsourced CO_2 emissions to Hebei (18% of total Tianjin's consumption-based emissions) and Inner Mongolia (12%), as well as Shandong (6%) and Liaoning (5%). However, Shanghai has more widespread effects of CO_2 emissions across China. Consumption in Shanghai caused emissions in its surrounding regions, such as Zhejiang (8% of Shanghai's consumption-based emissions) and Jiangsu (6%), but even larger shares from regions in north China, such as Hebei (9%), Shandong (7%), Henan (7%), and Inner Mongolia (4%). In contrast, Chongqing, one of the largest cities in western China, has less spillover effects compared with the other three megacities in the east. From the figure we can see that Chongqing mainly imported goods and embodied CO_2 emissions from its neighbors in the southwest of China, but the majority of imports were from Sichuan. The reason is that Chongqing was under Sichuan's administration before 1997 and thus still has very strong economic ties with Sichuan. Also, compared with the other three more developed cities in China, Chongqing still falls behind in economic terms.

Fig. 3 shows the extent to which each final demand category in each of the four megacities was responsible for the spillover effects of CO_2 emissions across China. From the figure we can see that more than half of the consumption-based emissions in Beijing, Shanghai, and Chongqing were induced by capital formation, i.e. road construction and housing development, of the cities. The share of emissions caused by capital formation in Tianjin was slightly smaller, but still accounted for 48%. This high contribution of capital investments in all megacities to CO_2 emissions is driven by the large scale economic growth and infrastructure requirements of a quickly urbanizing country, as well as driven by government policies (Minx et al., 2011; Zhang and Song, 2003). Nevertheless, household consumption is the second largest contributor among the find demand categories and ranges between 33% (Beijing) and 48% (Tianjin) of the total consumption-based emissions, which is a much smaller share than one would find in other countries. This

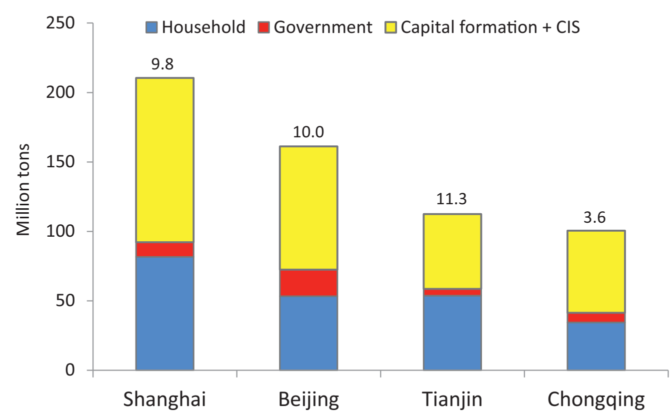

Fig. 3. Embodied emissions in major final demand categories (in million tons). The number on the top of each bar indicates per capita consumption-based emissions of each city (in ton).

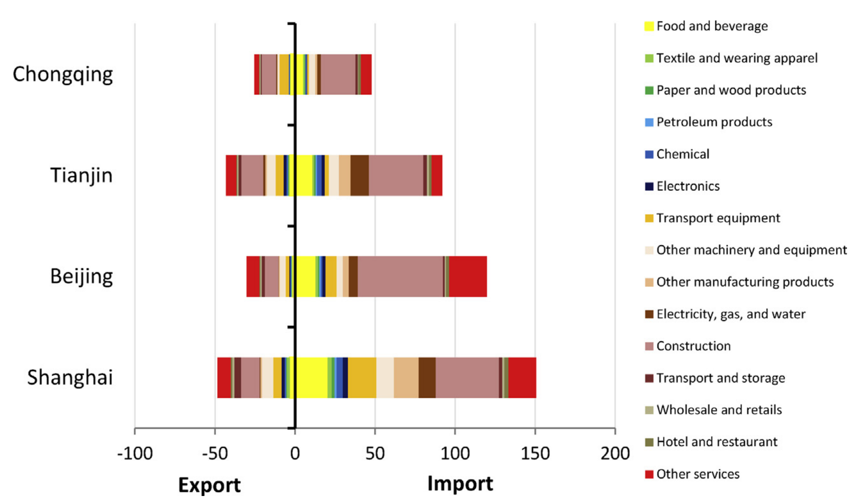

Fig. 4. Embodied CO_2 emissions in trade at the sectoral level (in million tons).

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result confirms previous research on carbon emissions in China (e.g. Feng et al., 2012; Guan et al., 2009; Hubacek et al., 2009; Minx et al., 2011; Peters et al., 2007). Beijing is a bit of an outlier with regards to its relatively large share of government expenditure being the capital city of China.

Fig. 4 shows at the sectoral level the embodied emissions in imports and exports of the four cities. For all four cities, the embodied emissions in imports were much larger than the emissions embodied in exports. For example, embodied emissions in Shanghai's imports were four times the amount embodied in its exports. The largest share of embodied carbon for imports can be attributed to the construction sector, owing to the large scale capital formation in Chinese cities. In addition, there is a relative large amount of embodied emissions in the imports of food sector in Shanghai, Beijing, and Tianjin, followed by other services, transport equipment, and other manufacturing products. However, in Chongqing, the share of embodied emissions in food imports was relatively small as the city still holds a large agricultural sector within its administrative boundary.

4. Conclusion and discussion

Urbanization has become a main force driving the increase of China's CO_2 emissions (Feng et al., 2012). In this study, we find that consumption in the four Chinese megacities not only causes CO_2 emissions within their own jurisdictional boundaries, but also imposes emissions to other regions via interregional supply chains. For example, close to 50% in Chongqing and more than 70% of consumption-based emissions in Beijing, Shanghai, and Tianjin are imported from other regions.

The major mechanisms for urbanization to drive CO_2 emissions rest on high demand for urban infrastructure and inter-regional transportation network developments, more carbon intensive urban life style enabled by higher income levels, and concentration of population with higher levels of income in comparison with their rural counterparts. The large scale urbanization and associated growth of wealth will continue driving the increase of China's consumption-based CO_2 emissions.

In this study, we confirmed the role of capital formation as the largest contributor to consumption-based emissions of these four cities. For example, in Shanghai embodied emissions in capital formation accounted for 56% of the total emissions in 2007. Large-scale capital investments have led to a structural composition of China's economy being heavily based on energy and emissions intensive electricity, metal, and cement production (Minx et al., 2011). It seems that urban infrastructure expansion along with the ongoing fast urbanization process will inevitably lead to more energy and emission intensive production in China. In particular, the urban infrastructure development will impose a large amount of emissions to its surrounding regions by importing construction-related inputs especially of those not suitable for long distance transportation. Therefore, to reduce consumption-based emissions, cities may cooperate with their neighbors to upgrade heavy industries by adopting more energy efficient production technologies in neighboring regions. Developing a clean development mechanism within China may provide an incentive for the cooperation between cities and their surrounding regions. For example under such a mechanism cities may get carbon credits if they invest in more advanced technologies in the heavy industries of their neighbors. But cities can also invest within their own boundaries to reduce carbon emissions at source and along the entire chain through using recyclable building materials and energy efficient buildings (Li et al., 2010). Energy efficient building may substantially reduce the overall energy use and thus associated CO_2 emissions with potentially negative cost (Minx et al., 2011). Another important part of the capital investment is transport infrastructure which has enormous long-term implications due to lock-in effects For example, due to relative sparse public transport infrastructure, people may have to rely on private car for commute and thus be "locked" into their transport emissions (Feng et al., 2010). Therefore, shifting consumption habits toward greener lifestyle would contribute to the reduction of urban consumption based emissions but requires an appropriate infrastructure. The infrastructure investments of today will determine the carbon emissions of the future thus a longer time horizon is required when analyzing carbon emissions and investments.

Closely related to capital investments through creating a physical environment partly determining consumption is household consumption. The fast growth of the urban population and changes from rural to urban lifestyles will further increase household consumption related CO_2 emissions. Our result shows that a large share of emissions was embodied in food imports associated with transport, food processing and refrigeration. An increasing share not accounted for in this study is the increasing dominance of meat based diets contributing to the carbon intensity of urban household consumption closely linked to increases in income mimicking similar trends in richer cities around the globe.

Although many studies have shown the usefulness of consumption-based accounting measures for understanding the drivers for emissions growth (e.g. Brizga et al., 2014; Peters et al., 2011; Wiedmann et al., 2010), few governments are using consumption-based indicators for their mitigation policies (Barrett et al., 2013). However, to better inform such policies it is important for cities to use consumption-based emission accounting allowing them to recognize and reduce carbon emissions within city boundaries and along the entire supply chains at least costs. The cross-boundary supply chains and cross-boundary mitigation responsibilities requires a coordination mitigation actions at larger scales and along global supply chains. Therefore, consumption-based carbon accounting is an important complementary indicator to the broadly used territory emissions for designing climate mitigation policies.

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