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Urban carbon footprints across scale: Important considerations for choosing system boundaries

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HIGHLIGHTS

- We develop a framework to consistently interpret carbon footprints of cities.
- Main destinations of outsourced carbon emissions from megacities are similar.
- Key infrastructure contributes > 70% of carbon emission in urban imports.
- Different carbon footprints show divergent sensitivities to mitigation policies.

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ABSTRACT

Cities dominate global anthropogenic carbon emissions. Here, we develop an approach to interpret carbon footprints of cities by focusing on their system boundaries, double counting recognition, spatial paths and policy sensitivities. Using four megacities in China as a case study, we quantify and map urban carbon footprints from various accounting perspectives: territorial carbon emissions, community-wide infrastructure carbon footprint, consumption-based carbon footprint, wider production carbon footprint, and full-scope carbon footprint. We find that the megacities' infrastructure carbon footprints are dominated by electricity-related emissions, whereas their consumption-based carbon footprints are significantly impacted by imports of both electricity and other products and services. Over 55% of the full-scope carbon footprints (sums of all three scopes) of Beijing and Shanghai can be attributed to upstream emissions, while in Chongqing and Tianjin territorial emissions are more important. Key urban infrastructure contributes over 70% to the total carbon emissions in import supply chains, determining the spatial paths and the carbon intensities of imports for these megacities. The main destinations of outsourced carbon emissions across the country from the megacities are found to be similar due to market domination of bulk suppliers of infrastructure-related and other carbon-intensive products. In addition, double counting of certain footprint indicators is considered small in this case, but could be amplified with increasing number of cities being assessed.

1. Introduction

About 55% of the world's population now resides in cities, and by 2050, the proportion of the world's urban population is expected to increase to 68% [1]. A large share of human production and consumption activities that impact global carbon budgets is concentrated in cities. About 70% of final energy is consumed by cities [2,3], and 71%–76% of final-energy-use carbon emissions are from urban sources [4]. Achieving the target of the Paris climate agreement to limit warming to well below 1.5 °C above pre-industrial levels

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requires a major cut of carbon emissions associated with urban activities. Accordingly, urban planners and decision-makers have started to collaborate and established city networks such as C40 [5] and Local Governments for Sustainability (ICLEI) [6] to develop standards, report their carbon emissions and measure progress toward climate mitigation.

Current approaches of carbon flow inventories portray different ranges of urban activities. Territorial inventories, which resemble the "production-based" emission inventories on the national scale, are often used by urban authorities to report carbon emissions [7]. There is wide agreement that a wider system boundary that goes beyond territorial inventory is important for deep decarbonisation [8,9]. This is because global supply chains often play a significant role in contributing to the growth of cities [10–12]. Selecting inventory boundaries for assessing temporal changes and spatial linkages of carbon emissions is an important aspect when assessing drivers of emissions and determining cities' share of responsibility and mitigation targets [13–15]. There are an increasing number of calls to include both urban carbon (i.e. in-boundary carbon flows, including fuels used within the urban boundary for production and consumption) and exo-urban carbon (trans-boundary carbon associated with the imports of products and services consumed or further processed in a city) when measuring climatic impacts of cities. Several approaches have been proposed for city-scale carbon footprint accounting that also include trans-boundary flows, such as territorial emissions plus electricity import and cross-boundary transportation [16–19], community-wide infrastructure footprints [20,21], consumption-based footprints [5,22,23], and footprints driven by final demands including exports [24–26]. Although several authors have made comparisons among some of these footprints [27,28], there are still ambiguities with respect to the coverage and assumption of these footprint indicators, during evaluation of carbon mitigation progress in cities.

There are workable schemes that can help provide a clearer view of the full picture of carbon footprinting for cities. One widely-used means of organizing the various accounting system boundaries at a local level was put forward by the Local Governments for Sustainability (ICLEI), the World Resources Institute (WRI) and C40 Cities Climate Leadership Group [29,30]. This method distinguishes urban greenhouse gas emissions into three scopes: Scope 1: emissions from fuel combustion or industrial processes within the city boundary; Scope 2: emissions from the use of electricity, heat, steam and/or cooling supplied to a city; and Scope 3: all other emissions that are released outside a city as a result of activities taking place within the city. However, to our knowledge there are only a handful of studies looking into the difference and implications of carbon footprint metrics used at city scale (e.g. [24,27,31]), and even less studies providing a decomposition into subsets of local and import supply chains. Given the sensitivity of the results dependent on the chosen approach and system boundaries, a systematic examination and comparison as provided by this paper has been long overdue. Moreover, no quantitative analyses have been performed for the possible double counting issue in carbon accounting and modelling at city scale, which may bias the outcome of urban carbon accounting [32]. In this paper, we aim to provide new insights on (1) how the subsets of urban and import supply chains are captured in carbon footprints differently and whether there is a double counting, (2) what is the role of decoupling urban infrastructure and consumption growth from carbon emissions given their significant contribution to total carbon flow paths, and (3) how sensitive are policy evaluations to the chosen carbon accounting approach.

We investigate the differences of five urban carbon footprint indicators within a consistent framework. These footprint indicators are territorial carbon emission (TCE), community-wide infrastructure carbon footprint (CIF), consumption-based carbon footprint (CBF), wider production carbon footprint (WPCF), and full-scope carbon footprint (FSCF). These footprint metrics are chosen as they are widely used and are instructive for how results change when changing accounting boundaries, ranging from the inclusion of only urban supply chains (i.e. TCE) to the combination of urban and import supply chains in part (i.e. CIF, CBF and WPCF), and finally to the coverage of all three scopes (i.e. FSCF). These metrics have been widely discussed in prior studies for their ability in portraying the carbon impact of a city [17,24,33]. Here we interpret them from a range of aspects such as system boundary, the problem of double counting, spatial paths of embodied carbon flows, and sensitivity of results due to the chosen footprint metrics. First, we characterize the impacts of urban activities on climate change within a consistent framework considering both local and import supply chains. Second, using four Chinese megacities (Beijing, Tianjin, Shanghai and Chongqing) as case studies, we account for all five types of carbon footprints based on the multi-regional input–output (MRIO) approach. The problem of double counting was also quantitatively evaluated when certain types of cities' carbon footprints are added together to quantify their total contribution to global climate change. Third, we map the infrastructure-related and consumption-based carbon flows across the country. Finally, we test the sensitivities of these carbon footprint indicators in response to carbon mitigation policies based on a scenario analysis considering different regulation measures. By doing so, we aim to generate a coherent interpretation of various urban carbon footprints and to reveal the underlying assumptions and implications of applying them to assessing the carbon impacts of cities.

2. Methods

2.1. Accounting system boundaries for urban carbon footprints

The following five types of carbon footprints are defined based on different system boundaries and differences in local and import supply chains related to production and consumption activities of a city:

(a) Territorial carbon emissions (TCE) (Scope 1) (e.g. [34–36]: cover in-boundary emissions (i.e. urban carbon) from fuel combustion and industrial processes in urban supply chains (USC), while all of the import supply chains (ISC) of goods and services are ignored.
(b) Community-wide infrastructure carbon footprint (CIF) (e.g. [8,20,37]): covers territorial emissions (urban carbon) plus infrastructure-related import supply chains (*exo*-urban carbon). The infrastructure considered in these studies includes provision of electricity, heating and transportation fuels, drinking water, construction materials (cement and iron/steel), wastewater/waste management, and food supply.
(c) Consumption-based carbon footprint (CBF) (e.g. [22,38,39]: covers entire supply-chain (both urban and *exo*-urban) emissions in infrastructure and non-infrastructure goods and services associated with consumption of households, the public sector and investment, while excluding supply chain emissions embodied in the production of exports of goods and services.
(d) Wider production carbon footprint (WPCF) ([26,28]; this study): accounts for territorial emissions plus emissions in import-related supply chains of infrastructure and non-infrastructure goods and services, with the exclusion of direct emissions from households and governments.
(e) Full-scope carbon footprint (FSCF) ([29,30]; this study): covers territorial emissions plus all import-related supply chain emissions (infrastructure and non-infrastructure), including supply chain emissions for export production (i.e. all urban and *exo*-urban carbon flows are included).

Confusion may occur given that these urban footprint terms are sometimes not fully in line with terms used in national accounting. Therefore, it is important to note which carbon flows are included or excluded when these approaches are applied to urban-level accounting. In Fig. 1, we visualize the differences in system boundaries of these five

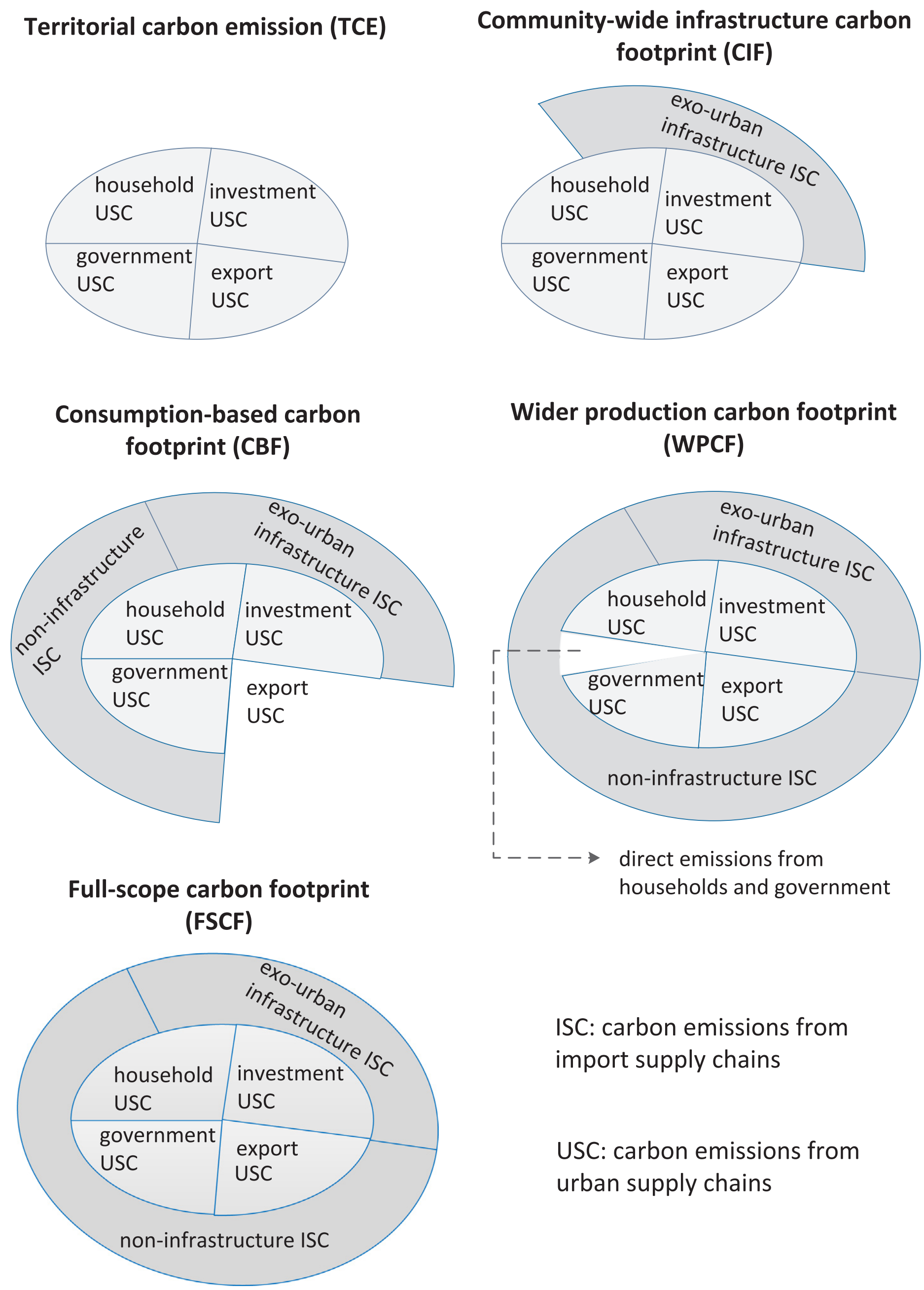

Fig. 1. Accounting system boundaries of five types of carbon footprints.

types of carbon footprints. Different combinations of subsets of emissions originating from local and import supply chains are highlighted in the diagram.

The main characteristics (i.e. coverage of scopes, main implications and possible overlap between cities) of these carbon footprints are shown in Table 1. These carbon footprints are likely to provide different results when assessing progress in urban decarbonization because of the divergence in accounting scopes. They are also responding differently to different policies. For instance, the CIF focuses on emission mitigation in infrastructure-related urban activities (i.e. food provision, supply of electricity, gas and water, transportation and wastewater/waste management). However, CBF focuses on mitigation of carbon emissions attributed to urban consumption, while the urban supply chains of export production are not considered. From the WPCF and FSCF perspectives, all activities that satisfy urban local consumption or urban export are included, regardless of whether they are associated with local or upstream supply chains. The issue of possible double counting is introduced in Section 2.3.

2.2. Accounting methods for urban carbon footprints

Territorial carbon emissions (TCE) are calculated following IPCC recommended guidelines [40] that associate local activities with respective carbon emission coefficients. We followed this convention and used input-output analysis (IOA) to allocate import-related carbon emissions to their system boundaries, that is, community-wide infrastructure carbon footprint (CIF), consumption-based carbon footprint (CBF), wider production carbon footprint (WPCF) and full-scope carbon footprint covering emissions in all three scopes (FSCF). IOA has been widely used for carbon footprinting at multiple spatial scales including cities [41–43]. The on-going progress of constructing sub-national input-output models is enhancing the accuracy of city-scale carbon

Table 1
Main characteristics of five types of carbon footprints.

Footprint type	Coverage of scopes	Main implication	Double counting
Territorial carbon emission (TCE)	Scope 1 emissions	Impact of local urban energy use and industrial processes on global climate change	No double counting
Community-wide infrastructure carbon footprint (CIF)	Scope 1 + Scope 2 + infrastructure-related Scope 3 emissions	Impact of key urban infrastructure	Footprints of cities cannot be simply added up
Consumption-based carbon footprint (CBF)	Scope 1 + Scope 2 + Scope 3 emissions driven by final consumption (export excluded)	Impact of urban consumption	No double counting
Wider production carbon footprint (WPCF)	Scope 1 (direct emissions from households excluded) + Scope 2 + Scope 3 emissions	Impact of production of urban products	Footprints of cities cannot be simply added up
Full-scope carbon footprint (FSCF)	Scope 1 + Scope 2 + Scope 3 emissions	Impact of urban production and consumption	Footprints of cities cannot be simply added up

accounting (e.g. [44,45]).

$$TCE = \sum_{i=1}\sum_{j=1} \text{activity}(i, j)\times \text{emission coefficient}(i, j) \tag{1}$$

$$CIF = k(I - A)^{-1}y^{infra-im} + TCE \tag{2}$$

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

$$WPCF = k(I - A)^{-1}(y^{fc} + y^{ex}) \tag{4}$$

$$FSCF = k(I - A)^{-1}(y^{fc} + y^{ex}) + C^{hg} \tag{5}$$

where TCE is determined by different types of energy use and industrial activities (i) of specific economic sectors (j) and respective carbon emission coefficients; k represents the sectoral carbon intensities of all regions in the MRIO model; I is the proper identify matrix; A is the matrix of direct technical coefficients; y^{fc} and y^{ex} represent final consumption (including residential consumption and capital formation) and export, respectively, in monetary values; C^{hg} refers to the direct emissions from households and government.

2.3. Double counting recognition

When applying the CIF, WPCF and FSCF to carbon accounting of multiple cities, double counting might pose a problem because these three footprint indicators include both import-related and export-related emissions to varying degrees. Double counting of carbon flows could arise if one tries to sum up the carbon footprints of two cities having inter-city trade flows between them, in which case the export from one city could also be the import to the next one. It should be noted that CIF, WPCF and FSCF can still be used in carbon accounting for cities individually and each of them has specific and complementary implications associated with carbon emission mitigation, only that these footprints of different cities cannot simply be added up to yield a "total climate impact". We provide a way to assess how big the double counting issue will be if cities' CIF, WPCF or FSCF are added up. Taking FSCF as an example, the identification of double counting ratio (DC) is formulated in Eqs. (6) and (7). The DC of all three footprints are assessed in an analogous way.

$$\begin{aligned}\sum_{r,s,\ldots}^{m} FSCF &= [FSCF_r' + f_{sr} + f_{rs}] + [FSCF_s' + f_{rs} + f_{sr}]+\ldots \\ &= [FSCF_r' + f_{sr} + FSCF_s' + f_{rs}] + [f_{rs} + f_{sr}] + \ldots\end{aligned} \tag{6}$$

$$DC_{r+s+\ldots} = \frac{f_{rs} + f_{sr} + \ldots}{FSCF_r + FSCF_s + \ldots} \times 100\% \tag{7}$$

where f_{sr} represents carbon flow from city s to city r (i.e. carbon emission related to import of r from s); $FSCF_r'$ is the full scope carbon footprint of city r excluding carbon flow originated from and to city s; $DC_{r+s+\ldots}$ denotes the double counting proportion of total carbon footprints added for m number of regions, which identify the repetitive computation of emission caused by bilateral trade.

2.4. Case study and scenario analysis

In 2012, Beijing, Tianjin, Shanghai and Chongqing (the metropolitan area), which are four major megacities in China, had populations of 21, 14, 24 and 29 million, respectively. With rapid economic growth and fast urbanization, they are development poles of China. Additionally, they have some of the highest per capita energy consumption in the nation, and have set ambitious goals of carbon emission mitigation for the coming decades. Some studies have shown that the territorial carbon emissions of Beijing peaked at around 2010 [46], but the carbon emissions related to imports increased considerably. This hides the actual degree of decarbonization from a life-cycle perspective. In this study, we interpret different types of carbon footprints using these four megacities as case studies. The framework proposed in this study can be applied to promotion of decarbonization of any city in the world.

Here, we conduct a scenario analysis to examine how carbon emissions relevant to these four megacities can be mitigated when different carbon footprint metrics are implemented. It can provide insights into how the selection of accounting metrics can impact the evaluation of carbon mitigation progress and the setting of mitigation goals. Three hypothetical scenarios are developed based on China's five-year carbon emission control plan (2015–2020), which is part of China's "13th Five-Year Plan." This plan decomposes the national goal of carbon emission intensity reduction to a regional level for better implementation. In our scenarios, we used these targets to set hypothetical carbon intensities, consumption volumes and consumption structure of Beijing. The setting of the five policy scenarios, i.e. Scenario 1 (technology improvement), Scenario 2 (reduced consumption), Scenario 3 (supplier change), Hybrid scenario I (Scenario 1 + 2), and Hybrid scenario II (Scenario 1 + 3) are described in Table 2. We used these scenarios to test the effects of production efficiencies, reduced final consumption and changes in domestic markets on the carbon footprints of the four megacities, then demonstrated how sensitive these carbon footprint indicators are to the implementation of carbon mitigation policies. It should be noted that there are other factors influencing carbon footprints that are not considered here. These hypothetical scenarios are not designated to simulate the real world, but to demonstrate the sensitivity of the carbon footprints.

2.5. Data

We used the multi-regional input–output (MRIO) table of China in 2012 for carbon footprints modelling, which consists of 31 regions with 42 sectors in each region [44]. We calculated the carbon emissions of all 31 regions based on province-level energy statistics in China [47], which are used to calculate sector-level carbon intensities of these regions, similar to the calculation process described in Shan et al [48]. Carbon emission factors of fossil fuels were from the IPCC reference values [40], while China-specific oxidization rates (The People's Republic of China National Greenhouse Gas Inventory) were used to avoid

Table 2
Settings of scenario analysis.

Scenarios	Change in carbon intensities (k)	Change in urban demand (y)
Scenario 1 (technology improvement)	Carbon intensities of five regions with the largest contribution to the cities' carbon imports are reduced by 20%	Business as usual
Scenario 2 (reduced consumption)	Business as usual	Final demand of the megacities in the five largest contributing regions (suppliers) is reduced by 20%
Scenario 3 (supplier change)	Business as usual	20% of final demand of the megacities in the five largest contributing regions (suppliers) is replaced by five other regions having the lowest carbon intensities
Hybrid scenario I (Scenario 1 + Scenario 2)	Carbon intensities of five regions having the largest carbon import are reduced by 20%	Final demand of the megacities in the five largest contributing regions (suppliers) is reduced by 20%
Hybrid scenario II (Scenario 1 + Scenario 3)	Carbon intensities of five regions having the largest carbon import are reduced by 20%	20% of final demand of the megacities in the five largest contributing regions (suppliers) is replaced by five other regions having the lowest carbon intensities

over-estimation of direct emissions. We also collected direct carbon emissions from households and governments based on official urban statistics. Since this study focuses on the comparison among different footprint metrics, we simply applied the Chinese technology assumption for all imports regarding the carbon accounting for the case cities, which could cause uncertainties in the results.

3. Results and discussion

3.1. Urban carbon footprints of different system boundaries

Fig. 2 shows the carbon footprints of four megacities in China from five different accounting perspectives. The total amounts of different types of carbon footprints varied greatly. Shanghai was found to have the largest total carbon footprint according to all accounting approaches, ranging from 220 Mt for TCE to 280 Mt for FSCF. Even though Tianjin and Chongqing have higher territorial carbon emissions than Beijing, Beijing's footprint (CBF) is bigger from a pure consumption-based perspective. The CBF of all four megacities in 2012 increased to varying degrees when compared with the numbers reported in 2007 [22,23,49]. Chongqing showed the largest increase in consumption-based footprint between 2007 and 2012 (+34%, or +46 Mt), while Beijing's CBF only increased by around 6% (+7 Mt), which was smaller than the increase reported by Shao et al. [50] using Eora data. The CIFs of the four megacities surpassed the territorial emissions by 70–144 Mt. Moreover, infrastructure-related imports added 57%–110% to the territorial carbon emissions of the four megacities, while non-infrastructure-related imports added 25%–51% as indicated by the wider production account. The WPCF covers over 95% of the full scope carbon footprint (i.e. FSCF, or Scope 1 + Scope 2 + Scope 3 emission) related to a city.

The difference between the community-wide infrastructure carbon footprint (CIF) and consumption-based carbon footprint shows that all four megacities are net-producers according to the interpretation in Chavez and Ramaswami [8] because they have a higher CIF than CBF (ranging from 28% to 74%, higher CFPs), among which Tianjin has the highest ratio of CIF to CBF. However, it should be noted that these cities might switch to net consumers in the future given their development trajectory and structural changes.

Fig. 2a also displays the decomposition of carbon footprints into accounting scopes that are widely used [29]. We found that Scope 2 was more significant than Scope 3 in terms of CIF, whereas both Scope 2 and Scope 3 have a prominent impact on CBF, WPCF and FSCF. Clearly the purchase of electricity in Scope 2 is a major part of infrastructure-related emissions. In comparison, non-electricity import (Scope 3) only accounts for 5%–8% of the total CIF. Around half of the consumption-based carbon footprint associated with Beijing, Tianjin and Shanghai are from Scope 3, while Chongqing has a smaller share in this scope (36% of the total). With higher income per capita, Beijing, Tianjin and Shanghai have a larger share of imported production in their CBFs than Chongqing. Over 85% of the CBF is caused by activities outside their administrative territories in these three megacities. About half of the WPCF is Scope 1 emissions, while the remainder is Scope 2 plus Scope 3 emissions. Beijing has the highest ratio of imports, in which Scope 3 alone accounts for 32% of its WPCF.

Fig. 2b describes the contribution of economic sectors (aggregated into eight categories for better visualization) to various carbon footprints. The detailed results of 42 economic sectors plus household direct emissions are shown in Fig. 3. Supply of electricity is the largest sector contributing to all types of carbon footprints for these four megacities. For example, electricity accounts for 40%–60% of the total territorial emission, indicating that there is a large share of power generated within cities in 2012. When including both locally-generated and purchased electricity, the contribution of this sector is even bigger (e.g. contributing 58%–71% to the total CIF). From a full-scope perspective, electricity supply explains about 44%–59% of the carbon footprint in all four megacities, with the highest proportion occurring in Tianjin. The contribution of manufacturing (as a whole) to territorial carbon emissions in Beijing (3%) was found to be drastically lower than that for the other three megacities (all > 15%). Manufacturing was the second largest contributor to CBF, WPCF and FSCF. For instance, manufacturing sectors accounted for around 30% of the megacities' WPCFs. These findings suggest the demand of manufacturing did not differ greatly among megacities, and only the required industrial production was outsourced to other regions at varying degrees. A large part of TCE and CIF is associated with transportation (between 18% and 23%) for Beijing and Shanghai, and its proportion declined to about 12% in FSCF. The impact from service sectors cannot be overlooked either. For example, the contribution of service sectors such as information transmission, computer services and software, financial services and research surpassed that of many manufacturing sectors from a full-scope accounting perspective. Although construction only contributed 2%–3% to the total carbon footprints in these cities, it has a higher proportion in FSCF than all manufacturing sectors other than food processing and metal smelting and rolling. Household direct emissions accounted for 16% of Beijing's total territorial emissions, but only about 5% in all megacities, and it adds 6%–10% to the total CBF, though this varies from city to city.

The carbon footprints of megacities are compared per capita and intensity [emissions per unit urban Gross Domestic Products (GDP)] (Fig. 2c). Shanghai had the highest per capita carbon footprint in every measurement, followed by Tianjin. Although Tianjin's total carbon footprint is smaller than that of Beijing, it has a much higher per capita footprint from all perspectives. Chongqing has the lowest per capita carbon footprint in all types except for territorial emissions, in which Beijing is slightly smaller. The footprint gap between cities is 11.7 t/capita considering all production and consumption activities of the cities (i.e. FSCF), while that of CIF is 8.0 t/capita. These findings suggest

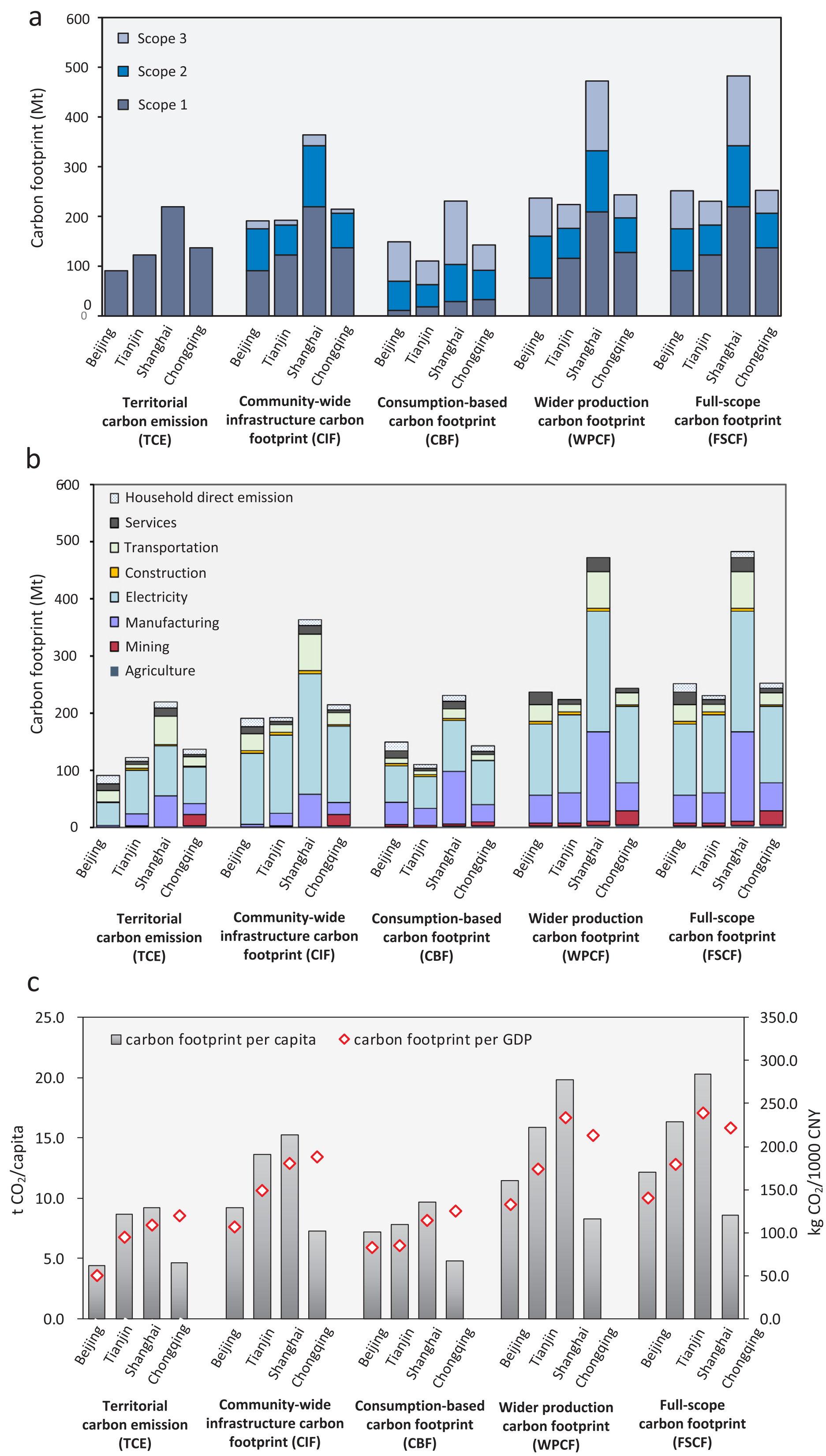

Fig. 2. Carbon footprints of four megacities (a) by accounting scope, (b) by economic sector and (c) per capita and per GDP.

that the key infrastructure needed for growth of all cities may result in major differences in carbon footprints. The CBF of Chongqing (4.8 t/capita) is only half of that of Shanghai, which has the highest CBF. This can be partially explained by the lower income of the population in Chingqing, which was on average 39 thousand CNY in 2012, compared to Shanghai's average of 85 thousand CNY. The continuous lowering of emission intensities is the major reason for this decline in per capita CBF [46]. However, the per capita CBF of Chongqing increased by 34%

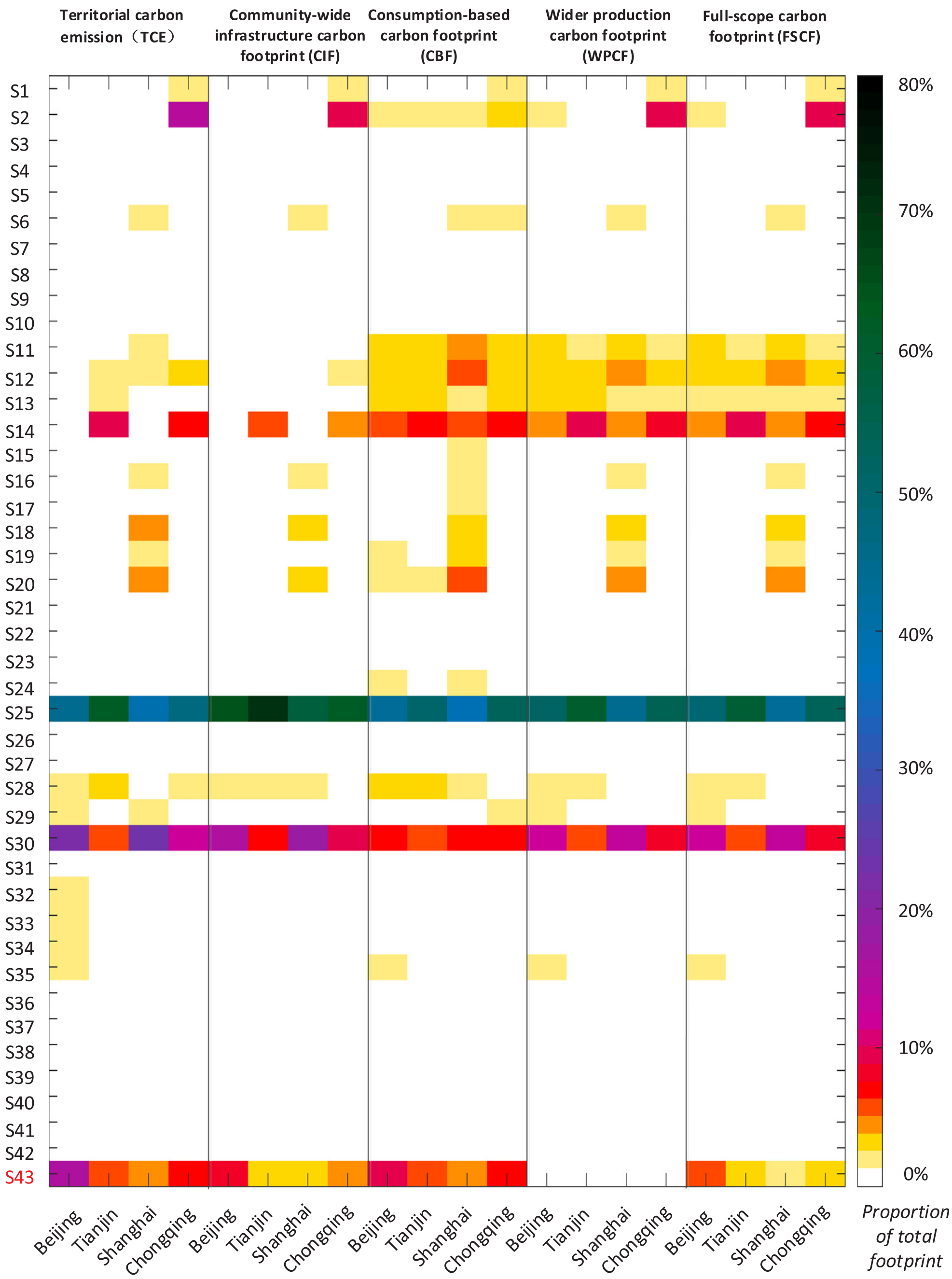

Fig. 3. Sector contribution to different types of carbon footprints of four Chinese megacities. Note: the 42 economic sectors are: (S1) Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy; (S2) Coal Mining and Dressing; (S3) Petroleum and Natural Gas Extraction; (S4) Ferrous and Nonferrous Metals Mining and Dressing; (S5) Non-metal and Other Minerals Mining and Dressing; (S6) Food Processing, Food Production, Beverage Production, Tobacco Processing; (S7) Textile Industry; (S8) Garments and Other Fiber Products, Leather, Furs, Down and Related Products; (S9) Timber Processing, Bamboo, Cane, Palm and Straw Products, Furniture Manufacturing; (S10) Papermaking and Paper Products, Printing and Record Medium Reproduction, Cultural, Educational and Sports Articles; (S11) Petroleum processing, coking and nuclear fuel processing; (S12) Raw Chemical Materials and Chemical Products, Medical and Pharmaceutical Products, Chemical Fiber, Rubber Products, Plastic Products (Chemical Products Related Industry); (S13) Non-metal Mineral Products; (S14) Smelting and Pressing of Ferrous and Nonferrous Metals; (S15) Metal Products; (S16) Ordinary Machinery; (S17) Equipment for Special Purposes; (S18) Transportation Equipment; (S19) Electric Equipment and Machinery; (S20) Electronic and Telecommunications Equipment; (S21) Instruments, Meters Cultural and Office Machinery; (S22) Manufacture of Other Manufactures; (S23) Scrap and waste; (S24) Metal Products, Machinery and Equipment Repair Services; (S25) Electric Power/Steam and Hot Water Production and Supply; (S26) Gas Production and Supply Industry; (S27) Water Production and Supply Industry; (S28) Construction Industry; (S29) Wholesale, Retail Trade; (S30) Transportation, Storage, Post; (S31) Hotels, Catering Service; (S32) Information Transmission, Computer services and Software; (S33) Financial Industry; (S34) Real Estate; (S35) Leasing and Commercial Services; (S36) Scientific research and technical services; (S37) Water conservancy, Environment and Public Facilities Management; (S38) Services to Households and Other Services; (S39) Education; (S40) Health, Social Security and Social Welfare; (S41) Culture, Sports and Entertainment; (S42) Public Management and Social Organization. S43 direct household emissions, which is calculated separately via local inventories.

from 2007 to 2012. One plausible reason for this increase is the rapid increase in urban consumption of Chongqing outpacing improvements in carbon efficiency during this period. The carbon footprint intensities of Chongqing are comparatively high from all accounting perspectives. It has the highest footprint intensity in terms of territorial, infrastructure-related and consumption-based accounting, followed by Shanghai and Tianjin. This "efficiency gap" between Beijing and Chongqing can also be seen from the divergence in CIF intensity (the latter is 1.8 times higher). The wider production-based perspective shows that when considering both upstream and local production chains (WPCF), Shanghai had a slightly higher carbon footprint intensity than Chongqing. This is mainly because the products imported to the city of Shanghai are more carbon-intensive than those imported to Chongqing.

Double counting occurs when cities' footprints including both import and export-related activities (in this case, CIF, WPCF and FSCF) are added up. Here, to make a succinct demonstration, we only quantitatively show the impact of double counting induced by bilateral trade between Beijing and the other three megacities rather than all possible combinations of cities (Fig. 4). In general, double counting has a bigger impact on the calculation with more cities involved, which holds for all footprint types. For example, on average 0.57% of carbon emissions are accounted for repeatedly when FSCFs of two cities are added up. In contrast, the double counting ratio increases to 0.74% and 0.82% for 3-city and 4-city situations, respectively. Although such impacts seem insignificant, they should be treated with caution given the accumulation and amplification effect with increasing numbers of cities and capturing denser trade networks between cities.

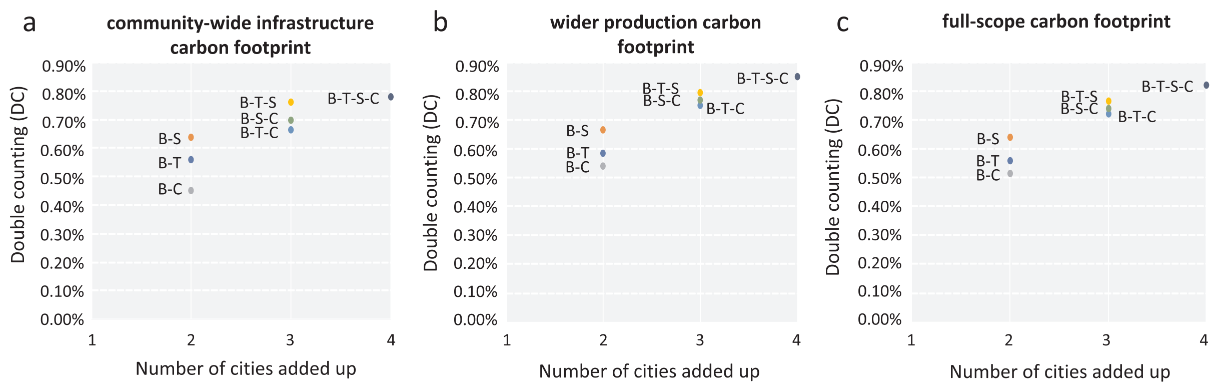

Fig. 4. Double counting ratios (DC) if certain footprints of Beijing and other cities are added up.

3.2. Spatial carbon transfer from different perspectives

We further illustrate the spatial carbon flows associated with infrastructure-related import and import for final consumption (excluding the fraction driven by export). We found that key urban infrastructure covers over 70% of the total import-related carbon emissions of the megacities (Fig. 5). The spatial distribution of carbon flows triggered by infrastructure-related imports was similar to the total import. Inner Mongolia contributed the largest share of infrastructure-related carbon imports to the four megacities, accounting for almost 10% of the total. This was mainly because of the cities' high reliance on electricity from thermal power plants in Inner Mongolia. The high carbon intensity in Inner Mongolia has made decreasing urban CIF challenging. Beijing and Tianjin have a higher proportion of carbon emission outsourced to provinces in north China and northeast China, while Shanghai's imports have a higher impact on Jiangsu.

In comparison, the differences in CBF-related import among cities were smaller than that of the total import (Fig. 6). The shares of CBF-

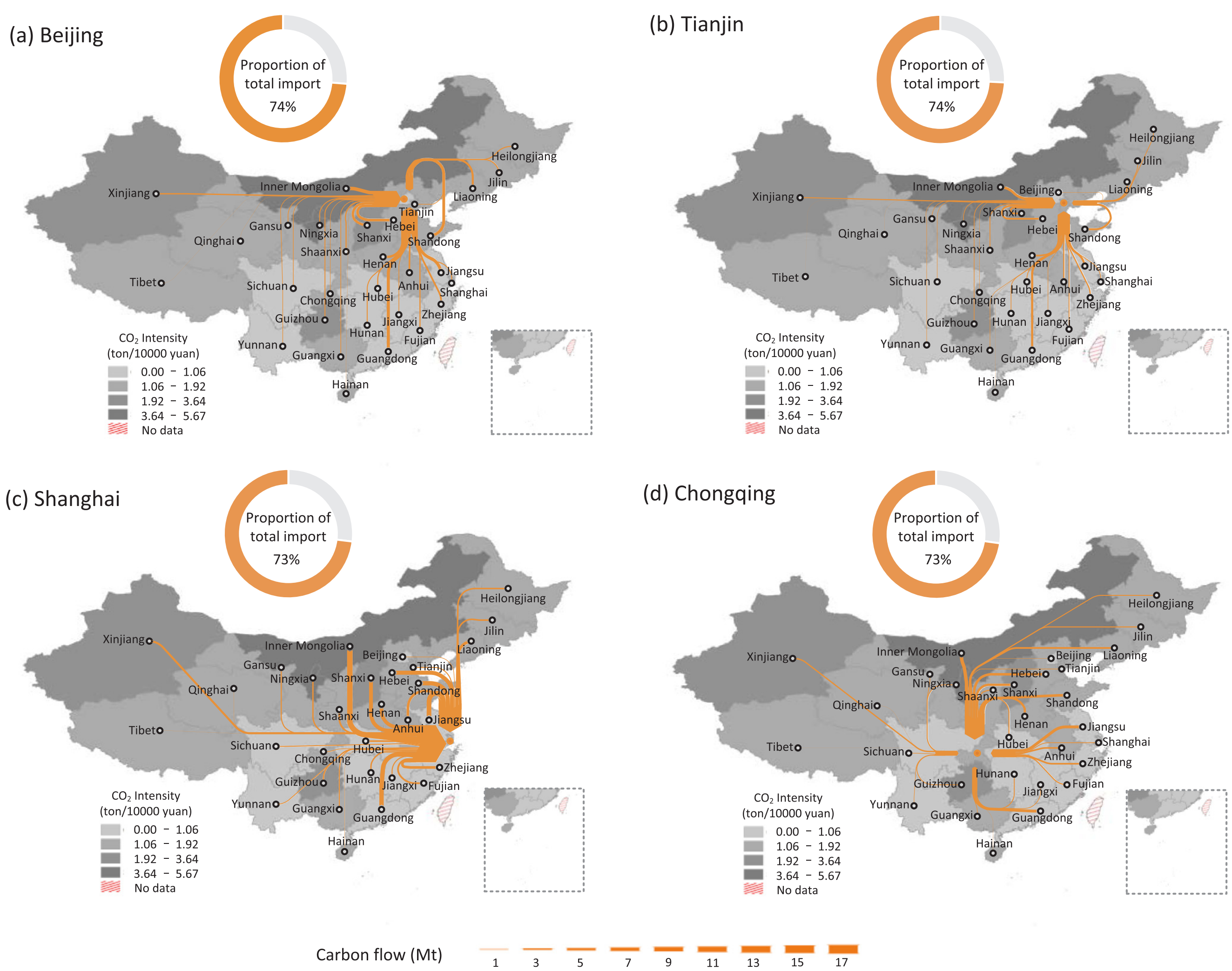

Fig. 5. Transfer of carbon emission across China driven by infrastructure-related import to four Chinese megacities.

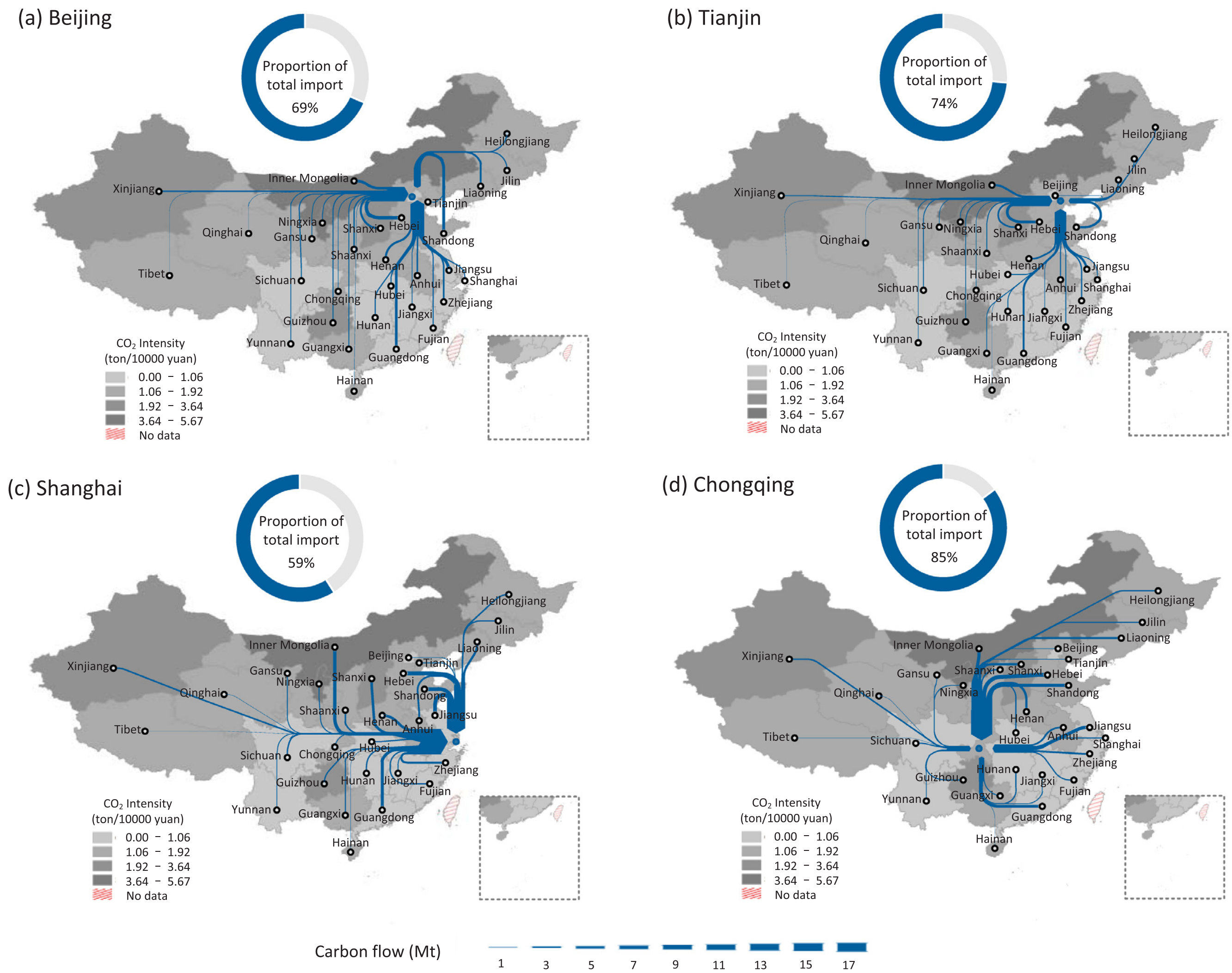

Fig. 6. Transfer of carbon emission across China driven by final consumption of four Chinese megacities (export is excluded).

related import varied significantly between cities. For instance, import related emissions for final consumption items in Chongqing are 85% of import related emissions. However, the import to Shanghai for local consumption only contributed 59% to the total import-related carbon emissions. All four cities have their largest share of consumption-based carbon footprint externalized to Hebei (9%) and Jiangsu (8%). The contributions of production in Guangdong and Inner Mongolia are approximately the same (7%) for all four megacities.

These carbon flow diagrams reveal details regarding how the spatial carbon exchanges triggered by various types of carbon footprints can provide complementary perspectives for optimizing upstream supply chains across the country. Cities should take a larger responsibility for slashing their carbon emissions aligned with their impacts and innovation capabilities. Tracking carbon flows based on a same accounting approach such as consumption-oriented or infrastructure-based account is important for cities to share the quota of global climate change mitigation.

3.3. Interpretation of carbon footprints under multiple scenarios

We further show how improvement in production efficiencies, consumption reduction and changes in domestic markets can contribute to carbon mitigation on a policy scenario analysis. The simulated changes in the CBF, CIF, WPCF and FSCF of the four megacities for the five scenarios are shown in Fig. 7. We found that Hybrid scenario I, a scenario combining efficiency gains and decreasing consumption, was superior to all other scenarios concerning mitigation of all five footprints. Scenario 1 (technology improvement) had a more mitigating effect than Scenario 2 (consumption saving) and Scenario 3 (supplier change) for all footprint indicators. These findings suggest that given the current carbon intensity of supply chains lowering the carbon intensities of the main suppliers of cities would be a more effective option than directly reducing demand for their products. Switching part of the final demand to less carbon-intensive suppliers is not as efficient as other approaches if the technical structure of the economy has not yet been fully adjusted.

The CBF, CIF, WPCF and FSCF of the four megacities responded to the policy scenarios differently. The full-scope carbon footprints (FSCFs) of all four cities were expected to be the most reduced of the footprints given their comprehensive system boundary. For example, the FSCF of Shanghai is expected to be reduced by 20 Mt, almost 1.5 times the reduction in the consumption-based footprint (CBF). However, CBF is the footprint indicator most sensitive to technology improvement, consumption saving and supplier change. For example, the CBFs of cities are expected to be reduced by 5.1%–6.0% in Scenario 1 (technology improvement) and 1.2%–1.8% Scenario 2 (consumption saving). In comparison, CIF was found to be relatively insensitive to these regulations, showing mitigation rates of only 2.6%–3.7% and 0.6%–1.0%, respectively, for all scenarios. These findings indicate that changing carbon intensities of several upstream regions is less effective

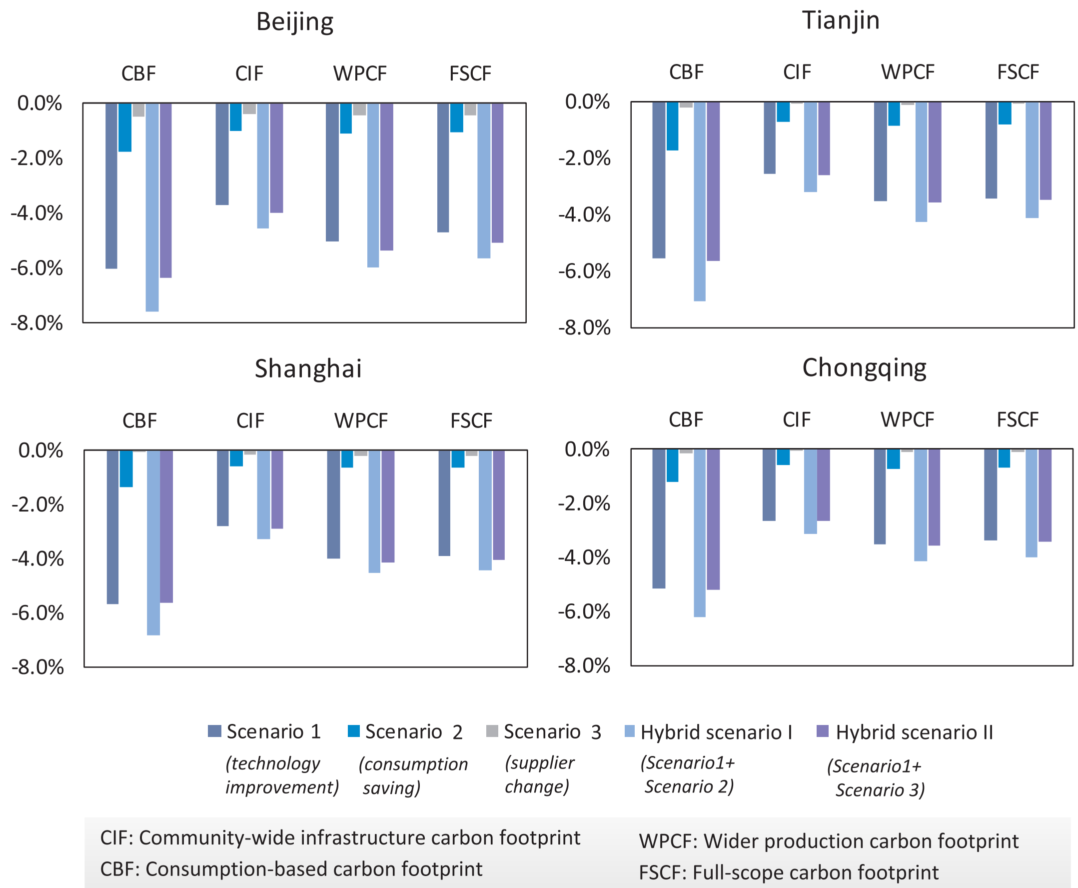

Fig. 7. Changes in carbon footprints of four megacities under multiple policy scenarios compared with accounting results in 2012.

in carbon mitigation related to infrastructure for these cities if their territorial emissions remained unchanged. The scenario analysis clearly shows that regulating consumption or switching upstream suppliers alone may not have a great impact on urban decarbonization, but they still play an important role in regulating consumption-based carbon footprints. To enable more efficient mitigation, they should be jointly implemented while improving carbon efficiencies.

In order to have a reasonable comparison, it is suggested that all cities report the same type of footprint or inventory protocol for their carbon emissions (as recommended by [29,30]). This will facilitate a consistent evaluation of carbon mitigation progress in cities, worldwide. These carbon footprint metrics can provide benchmarks for meaningful and achievable mitigation goals considering a city's socioeconomic characteristics, developmental stage, economic structure, and policy reach, i.e. the amount of control or influence they have over activities within its administrative boundaries and associated import supply chains. For example, TCE can guide mitigation policies on emissions from local manufacturing and household energy use becaus it highlights production for local supply and fossil fuels used in households, while CBF can target the optimization of both local and import supply chains. From a full supply chain perspective, WPCF and FSCF may be used in "next-stage" mitigation actions in order to maximize the power of deep decarbonization of the global economy. Different types of carbon footprints can complement each other in urging cities to set ambitious mitigation targets while perusing economic development.

4. Conclusions

The role of cities in combating climate change is well recognized [51–54]; however, there is also a long-standing debate regarding the possible overestimation of the contribution of cities as a whole [55,56] and the lower per capita carbon emissions in many cities relative to their average national level when looking at only scope 1 emissions [34]. However, this debate has been muddied by the use of different system boundaries, and this topic can only be properly addressed by acknowledging the importance of system boundaries in carbon footprint accounting.

This paper provides a systemic evaluation of carbon footprints by tracking all subsets of in-boundary and trans-boundary carbon flows related to a city. By extending the concepts established in a number of studies (e.g. [8,31,33,57]), we show the system boundaries and spatial impacts of five different types of footprints; namely, territorial carbon emission (TCE), community-wide infrastructure carbon footprint (CIF), consumption-based carbon footprint (CBF), wider production carbon footprint (WPCF) and full-scope carbon footprint (FSCF), using four Chinese megacities as a case study. We found that:

(1). Infrastructure-related import added 57%–110% to the territorial carbon emission for the four Chinese megacities, while non-infrastructure-related import added another 25%–51% to territorial carbon emissions. Scope 2 emissions were dominant in community-wide infrastructure carbon footprint, whereas both Scope 2 and Scope 3 emissions had a significant impact on consumption-based carbon. About half of the cities' wider production carbon footprint was Scope 1 emissions, while the remainder was Scope 2 plus Scope 3 emissions.

(2). The per capita "footprint gap" among cities varied notably with different accounting boundaries. The biggest was 11.7 t/capita considering all production and consumption activities of the cities (i.e. FSCF), which was more than double the gap of territorial carbon emissions and consumption-based carbon footprint. Household direct emissions added 6%–10% to the total consumption-based carbon footprint, which has often been neglected in consumption-based accounts. These were found to provide an important factor for different urban carbon footprints.

(3). The main destinations of outsourced carbon emissions across the country from the four megacities were similar. Key urban infrastructure required by all cities covered over 70% of their total import-related carbon emissions; therefore, community-wide infrastructure carbon footprint is able to capture the main flows of spatial carbon leakage. Tracking carbon flows with a specific focus such as evaluation of consumption-oriented or infrastructure-based carbon is an important strategy when designing mitigation policies aligned with city typologies and developmental stages.

(4). Different types of carbon footprints respond differently to regional mitigation policies. In the context of the four megacities and their supply chains, the consumption-based carbon footprint was more sensitive to changes in carbon intensities, consumption volume and structure in the scenarios than the other types of footprints. In addition to improving production efficiency, influencing consumption and switching upstream suppliers can provide complementary measures for footprint mitigation. We strongly emphasize that the choice of a footprint metric will influence the outcome of carbon accounting and policy evaluation. Therefore, comparable and standardized approaches integrating insights from these complementary accounting approaches are called for in supporting deep urban decarbonization.

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