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Leveraging opportunity of low carbon transition by super-emitter cities in China

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ABSTRACT

Chinese cities are core in the national carbon mitigation and largely affect global decarbonisation initiatives, yet disparities between cities challenge country-wide progress. Low-carbon transition should preferably lead to a convergence of both equity and mitigation targets among cities. Inter-city supply chains that link the production and consumption of cities are a factor in shaping inequality and mitigation but less considered aggregately. Here, we modelled supply chains of 309 Chinese cities for 2012 to quantify carbon footprint inequality, as well as explored a leverage opportunity to achieve an inclusive low-carbon transition. We revealed significant carbon inequalities: the 10 richest cities in China have per capita carbon footprints comparable to the US level, while half of the Chinese cities sit below the global average. Inter-city supply chains in China, which are associated with 80% of carbon emissions, imply substantial carbon leakage risks and also contribute to socioeconomic disparities. However, the significant carbon inequality implies a leveraging opportunity that substantial mitigation can be achieved by 32 super-emitting cities. If the super-emitting cities adopt their differentiated mitigation pathway based on affluence, industrial structure, and role of supply chains, up to 1.4 Gt carbon quota can be created, raising 30% of the projected carbon quota to carbon peak. The additional carbon quota allows the average living standard of the other 60% of Chinese people to reach an upper-middle-income level, highlighting collaborative mechanism at the city level has a great potential to lead to a convergence of both equity and mitigation targets.

1. Introduction

As home to more than 4 billion people globally, cities are central to the tasks of reducing inequality and acting on climate change—

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respectively, the UN Sustainable Development Goals (SDGs) 10 (reducing inequality) and 13 (climate actions). In China, cities contribute 85% of national CO_2 emissions and 20% of global CO_2 emissions [1–3]. China has pledged a series of mitigation targets (e.g., reaching peak carbon by 2030 and carbon neutrality by 2060), with low-carbon transition in cities at their core and recognized as key to their success. However, significant disparities in development exist between Chinese cities with different roles in inter-city supply chains [4–6]. Thus the low-carbon transition should preferably lead to a convergence of equity and mitigation [7–9]. However, the benefits and costs of the low-carbon transition are not proportionately distributed, which risks the creation of new winners and losers. Less developed cities with "dirty" energy records face relatively high mitigation costs related to the transition compared to rich cities with less carbon-intensive industries; this disparity compromises poorer cities' development prospects and challenges regional equity [10]. On the other hand, reducing disparity demands that industrialisation accelerates in less developed cities, which inevitably raises carbon emissions and presents a challenge to mitigation targets [11]. Hence, how to deliver low carbon and inclusive transition for cities significantly concerns developing countries with fast urbanisation.

The divergence between the two SDGs (10 and 13) points to the need for a low-carbon transition that incorporates equity concerns into the mitigation paradigm, and highlights possibilities for collaboration [12,13]. Cities are increasingly connected, as inter-city supply chains link their production and consumption activities to sustain their economic growth. As a result, mitigation efforts in one city could affect others throughout the supply chains, with the potential to generate unintended consequences [14,15]. Hence, an inclusive low-carbon transition for cities will demand neither a "one-size-fits-all" strategy nor one where individual cities act alone. It must respect collective yet differentiated responsibilities, taking into account the heterogeneity of cities [16–18]. Recent researches highlight how the exclusion of inter-city supply chains has compromised mitigation efforts and collaboration prospects [19–21]. Despite numerous studies of carbon footprints in China, most focus on the regional level, and thereby fail to capture the distinct differences in cities' footprints. Moreover, most city-level studies primarily focus on mitigation in individual cities and fail to factor in inter-city supply chains [5,22–24]. The few studies explored mitigation implications by explicitly focusing on the spillover effects of supply chains [25–29], and they focused on a few pilot cities, and thus cannot offer holistic insights for city-level mitigation efforts in China.

To bridge the gap, we quantified the most comprehensive city-level carbon footprint in China by tracing inter-city carbon flows and illustrated carbon inequality among the cities by constructing a new multi-regional input-output (MRIO) model to link the economic activities of the 309 cities (90% of Chinese cities). Due to the data availability, we show a snapshot of the city-level carbon footprint for 2012. The scope of our study focuses on carbon emissions happened in China, excluding imports-related emissions, due to relative insignificance compared to domestic emissions [30]. In considering the socioeconomic status, size and structure of the economy, and the supply chains of all the cities, we highlighted the leveraging opportunities of key super-emitting cities to both bridge regional disparities and contribute to mitigation (here, we identify that super-emitting cities are those whose carbon footprint or production-based emissions are >1% of total national emissions). The opportunities in the allocation of carbon quota generated by key super-emitters supplement the current carbon trade scheme. The carbon footprint in this study indicates the carbon emissions driven by both household consumption and capital investment activities. Notably, the terms "city" and "city boundary" can have quite different meanings. Cities defined as built-up areas have deep connections to their hinterlands in terms of products and services provision. Industrial structures between the built-up area and hinterland are very different, where the energy sector, heavy manufacturing, and mining sector are more located in the hinterlands and tertiary sectors are more concentrated in the built-up areas. However, our study adopts "metropolitan area" as the definition of a city, which includes both urban and peri-urban areas (or hinterlands). This is consistent with how cities are defined in Chinese statistical data. We take into account the carbon emissions released by all activities carried out within the city's administrative unit (including built-up areas and hinterlands). For instance, Guangzhou's carbon emissions include those from the city's built-up parts as well as its rural hinterland. The NUTS3 categorization (nomenclature of territorial units for statistics) used by the European Union (EU) is comparable to the definition of a city. In addition, carbon emissions in this paper refer to emissions from energy combustion and industrial processing (e.g., heating limestone). Emissions from other sources (e.g., land use change) are not in our scope, due to data unavailability. In this paper, the term "supply chain" refers to transactions between different industries instead of purchasing at the firm level.

2. Method

2.1. The city-level MRIO table of Chinese cities

To explore inter-city supply chains, we constructed a city-level multi-regional input-output (MRIO) table for 309 cities in 2012. This table covers 92% of Chinese cities and is the first of its type to offer a holistic view of China's inter-city supply chains. The table covers 313 regions, including 309 cities and 4 provinces (Qinghai, Yunnan, Hainan, and Tibet) of Chinese mainland (except Hong Kong, Macao, and Taiwan due to data unavailability), and 42 socioeconomic sectors. Chinese mainland has 27 provinces and 4 municipalities (Beijing, Shanghai, Tianjin, and Chongqing).

The overall procedure for constructing the table can be divided into two steps: (1) constructing city-level MRIO tables for 23 provinces (China has 31 in total); (2) nesting all city-level MRIO tables for the 23 provinces into a provincial MRIO table of China linking each city with others. Due to issues of data availability, it is difficult to create city-level MRIO tables for four provinces (Qinghai, Yunnan, Hainan, and Tibet). As a result, they are listed as provinces in the final city-level MRIO table. The details of the MRIO table compilation can be found in our previous work [14]. Due to different data sources and consolidation processes, the uncertainty of the MRIO model is a concern for model users. Our previous analysis of the uncertainty of the city-level MRIO model has shown that the method is solid to generate an accurate MRIO table [14,31].

To compile a city-level MRIO table for a given province, we follow the entropy-based method of compilation geared to this purpose [14]. Briefly, this can be divided into several steps: (1) we first collect economic statistics data for the 309 cities, including sectoral output, value-added, gross domestic product (GDP), and trade data from statistics books for each city and China customs database. The collected city-level data are then calibrated with provincial data and national data—a necessity, due to the inconsistency in statistics data between agencies at different levels [32]. (2) We estimate supply and demand for the cities by sector in a given province, using the calibrated city-level total output data and trade data. (3) Then, for each sector, the estimated demand and supply are disaggregated using the maximum entropy model into self-supplied supply, supplied from cities in the province, supplied from cities out of the province, and self-supplied demand, demand from cities in the province, demand from cities out of the province. (4) We apply the cross-entropy model to estimate the single-regional input-output (SRIO) table for each city based on the outcomes in step (3) and the provincial SRIO table. (5) We use the maximum entropy model again to estimate the inter-city trade flow by sector using the supply and demand from cities in a given province estimated in step (3). (6) We link all city-level SRIO tables and estimated trade flows to generate a city-level MRIO table for the given province; (7) We repeat all the steps to generate 23 city-level MRIO tables and then nest them into the China provincial MRIO table. The nesting approach has been used to link different MRIOs together [33–35]. Specific details of the city-level MRIO table construction can be found in our previous work [14]. The constructed table can be found in China Emission Accounts and Datasets (CEADs) (www.ceads.net).

We categorised all 309 cities into five quintile groups according to affluence and economic structure, with the top quintile representing the richest cities (>$7000/capita) (Fig. S1 online). Beyond affluence, the economic structures of cities also matter in the distribution of carbon footprints and have essential implications for low-carbon transition strategies. We grouped 309 cities according to their industrial structures using the *K*-means cluster into five types: agricultural, low-added light manufacturing, low-added heavy manufacturing, energy and resource, and high-tech (Fig. S2 online).

2.2. Environmentally extended input-output accounting

To calculate the carbon footprint (or consumption-based emissions), we employed the environmentally extended input-output model (EEIO) [36,37]. The model has been widely applied as a tool to trace spillover effects (such as carbon footprints) through supply chains and to identify regional heterogeneity [38–41]. The model links the activities in final demands (namely household expenditure, capital formation, and inventory changes) with production activities as well as associated environmental impacts.

The basic equation of the input-output (IO) model can be expressed as follows:

$$\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{F}, \quad (1)$$

where $\boldsymbol{X}$ represents the vector of total output in each sector, and $\boldsymbol{A}$ represents the direct technical coefficient matrix. The elements of $\boldsymbol{A}$ represent the required input from sector i to produce a unit of output in sector j. $\boldsymbol{I}$ is the identity matrix, while $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the Leontief inverse matrix. $\boldsymbol{F}$ is final demand (including household consumption, government consumption, capital formation, and the change of inventory), where f_i^{rs} (f is the element of $\boldsymbol{F}$) refers to the final demand produced in region r for sector i consumed in region s.

$$\boldsymbol{C} = \boldsymbol{E}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{F}, \quad (2)$$

where $\boldsymbol{A}$ is the technical coefficient which is calculated as $a^{rs} = (z_{ij}^{rs}/x_j^s)$ which refers to the ratio of supply from sector i in city r in total input to sustain the production of sector j in city s; $\boldsymbol{F}$ is the total final demand (aggregating household consumption, government consumption, capital formation, and the change of inventory). Therefore, all of these parameters are derived from the MRIO table (the layout can be found in Fig. S3 online). $\boldsymbol{E}$ is the carbon inventory for all sectors in all cities. The equation represents the carbon footprints generated due to final demands. Consumption-based emissions here refer to carbon emissions induced by total final demands via supply chains.

2.3. Carbon inventory construction

We constructed the production-based emission inventories of cities based on our previously developed methods [42,43]. The emission inventory includes Intergovernmental Panel on Climate Change (IPCC) administrative-territorial (scope 1) emissions from 17 types of fossil fuels and industrial processes and is compiled using 47 socioeconomic sectors, which is consistent with our national and provincial emission accounts [44,45]. The method offers a systematic way to scale down the provincial energy balance sheets and sectoral energy consumption to the city level with auxiliary socio-economic data such as industrial output, population, and GDP. It categorises the different cases based on different data availability.

The emissions are calculated following the IPCC national greenhouse gas (GHG) inventory guidelines [42,46,47]:

$$\mathrm{CE} = \sum\sum \mathrm{AD}_{ij} \times \mathrm{EF}_{ij}, \quad (3)$$

where CE represents the total aggregated CO_2 emissions from energy type i used by sector j. AD_{ij} represents the fossil fuel i combusted in sector j and industrial processing, measured in physical units, and EF_{ij} represents the emission factors for the corresponding fossil fuels and industrial products. The emission factors are collected from Ref. [48], which could reflect China's coal quality better than the default shown by IPCC. We compiled the emission inventories of 244 cities; due to data unavailability, the emissions of the remaining 65 cities are estimated based on the carbon intensity from the province they belong to and their sectoral outputs. The data and uncertain discussion can be found in our previous work [49]. The carbon inventory at the city level can be also sourced from China Emission Accounts and Datasets (CEADs) (www.ceads.net).

2.4. Industry structure cluster

Using the *K*-means cluster algorithm, we categorized the 309 cities into five types, according to their economic structure: agricultural, light manufacturing, heavy manufacturing, energy, and high-tech (the distribution can be found in Fig. 4S online). The cluster is based on the share of sectoral value-added in GDP for each city. Specifically, we first aggregated 42 sectors into the 5 categories indicated above, then calculated the proportion of value-added in local GDP for each sector. We applied the *K*-means cluster algorithm to group cities, taking into account comprehensive multi-indicators—that is, the shares of value-added in GDP for the five sectoral groups.

The *K*-means algorithm has recently been used in regional studies [5,50,51]. The method considers each sample in a dataset as a point in *n*-dimensional space and chooses *k* centres, then assigns each point to the cluster. The central point is the average of all the points in the cluster: its coordinates are the arithmetic mean for each dimension separately over all the points in the cluster. The metric to measure the distance between points and central points in each cluster varies, but a previous study suggested the simple Euclidian distance could generate a better outcome [52]. We thus adopted the Euclidian distance for our study.

2.5. Mitigation scenarios

Our mitigation scenarios are aligned with the principle of equity and carbon peak. The collaborative strategy is based on the notation "The right to carbon emission is the right to development". The strategy thus is to apply mitigation measures to a few super emitters subject to their industrial and supply chain characteristics. The carbon quota generated by super emitters therefore can be reallocated to less developed cities for their growth.

32 supper emitters are grouped into three types in terms of mitigation pathways. Type 1 cities are 14 cities that have higher consumption-based emissions and should adopt demand-based strategies. Type 2 cities are 9 cities that have higher production-based emissions and should follow technology-based strategies.

Type 3 cities are 9 cities that have both high consumption-based and production-based emissions and need to adopt hybrid strategies that should involve both technological and demand-side solutions.

We set the light and deep mitigation scenarios for technological and demand mitigation, respectively (a comparison figure can be found in Fig. S4 online). When applying the mitigation measures, 18 super-emitters (technology-side and hybrid strategy cities, or type 2 + type 3 cities) adopt technological solutions. With technological solutions, light mitigation refers to reducing the carbon intensity of key sectors to match the national average; deep mitigation denotes reducing carbon intensity to match the global average. When the carbon intensity of a sector is higher than the benchmark—that is, the national average or the global average—the benchmark is used as the target for achievement. The carbon intensity of a sector is kept when it is lower than the benchmark. 23 Cities (demand-side and hybrid strategy cities, or type 1 + type 2 cities) adopt demand-based solutions. For demand-side mitigation, light mitigation assumes that the share of capital formation of 23 super-emitters (14 cities with demand-based strategies and 9 with hybrid strategies) is reduced to the average level of the global megacities. Deep mitigation expands the boundary of cities and assumes that the share of all high-tech cities among the richest cities (that is, the top quintile) reduces to the global level. In estimating the carbon deficit enabling the growth of less affluent cities, we only assume the per capita demand rising, while carbon intensity and production structure are not changed.

3. Results

3.1. Inequality in carbon footprint between Chinese cities

The carbon footprints of Chinese cities show a large disparity due to an uneven distribution of economic growth and population. The carbon footprints of a city measure its life-cycle carbon emissions generated by production to meet economic demands (such as household consumption and capital formation). Fig. 1a presents the distribution of carbon footprints of the 309 Chinese cities studied. In total, 309 Chinese cities lead to 7324 Mt carbon emissions, accounting for 81% of national emissions. The 10 cities with the largest carbon footprints generated 17% (1263 Mt) of the national carbon footprint, equivalent to the annual emissions of Russia, the world's fourth-largest emitter. Affluent cities, especially global megacities such as Shanghai and Beijing, have large carbon footprints. The most affluent 63 cities (the top quintile) account for 47.7% of total carbon footprints (3462 Mt, equivalent to that of the European Union sans the United Kingdom [53]). The population of these cities only accounts for 25.6% of the total population of China but produces 46.3% of total GDP (Fig. S5 online). By contrast, roughly 60% of China's population—that is, those living in cities where the per capita demand is less than US$5300—are only responsible for 30% of carbon footprints. This disproportionality is extreme for marginalised cities (the last quintile cities): they are home to 18.3% of the population but are responsible for only 6.4% of the overall carbon footprint.

This disproportionality is largely attributed to China's investment-driven urbanisation over the past decades [6,30,54]. In Chinese cities where carbon footprints are dominated by capital investments, these account for 65% of the total footprint (4721 Mt); The pattern of urbanisation is highly uneven, with large-scale infrastructure investments more concentrated in affluent megacities [55]. Roughly 50% of carbon footprints are found in the top quintile cities (2266 Mt). This carbon inequality, shaped by investment, reflects the citizens in the rich cities could benefit more from well-constructed infrastructures. Better capital investment leads to a decency of living, which is not just about high income (or high consumption), but also about decent housing and accessible infrastructure (e.g., better road network). For example, road density in rich cities is much higher than the less developed cities (e.g., Shanghai with 7.1 km/km^2 is almost two times than Ürümqi (3.4 km/km^2), the less affluent capital city in the west of China) [56].

This level of carbon inequality not only indicates the great responsibility of citizens living in rich cities, due to higher consumption. It also reveals the large disparity in the living standard of citizens living in rich and poorer cities. The gap in per capita footprints between cities is extremely large (Fig. 1b). We found 153 cities with per capita carbon footprints larger than the global average (4.4 t/cap): those for the top 10 cities are higher than the US equivalent (18.0 t/cap), and those for 63 cities are higher than the EU equivalent (8.3 t/cap). Top quintile cities show an average of 12.6 t/cap, nearly twice that of second quintile cities (6.7 t/cap), and six times more than the bottom quintile (2.0 t/cap). There are 38 less developed cities with per capita footprints of less than 2.0 t/cap, equivalent to the level of lower-middle-income countries such as India and Sri Lanka.

Many of the cities with the largest per capita footprint are sited in the north of China (Fig. 1c), a result of the size and structure of the local economy as well as the distribution of natural resources. Most of China's carbon-intensive heavy manufacturing (of iron and steel, for instance) and resource extraction such as coal mining takes place in its northern cities. Ordos, for example, has a per capita footprint of 36.0 t/cap and is one of the country's key energy centres, responsible for 17% of overall national coal production and 24% of natural gas production.

The finding is compatible with the global pattern, which shows that the world's largest per capita carbon emitters are major energy-producing countries such as Qatar (38.9 t/cap). Affluent megacities such as Beijing (6.5 t/cap), Shanghai (5.2 t/cap), and Shenzhen (8.9 t/cap) have much lower per capita carbon footprints, due to their service-dominated economic structures and dense population[57]. Marginalised cities in the west of China have footprints at the level of cities in the Global South. For instance, the footprint of Bazhong, the most marginalised city in Sichuan, is equivalent to Vietnam (1.3 t/cap).

3.2. Inter-city supply chains contributing to socioeconomic disparity

Inter-city supply chains play a significant role in shaping the distribution of carbon footprints. Some 80% of the total carbon footprint (about 5800 Mt, equivalent to the national emissions of the United States) is embodied in these supply chains. The large outsourced emissions suggest the scale of production fragmentation, where cities sustain their demands produced by others. It implies the potential challenge of carbon leakages, as affluent cities may outsource carbon-intensive products from less developed cities.

Previous studies found that carbon flows transfer primarily from the less developed western provinces to affluent coastal regions [58–60]. At the city level, however, we found the carbon flows are more concentrated between rich cities than between rich and poorer ones (Fig. 2a), as poor cities are often under-industrialised. 16% of total inter-city carbon flows (915 Mt) take place between top quintile cities, followed by 11% from the second quintile to top quintile cities (641 Mt). Although half the carbon footprints of rich cities are outsourced from others (2728 Mt), we found that carbon flows from top quintile cities make up the largest components in outsourced emissions of other quintile cities, indicating that rich cities are not only the leading consumers but also play a major role of producers to other cities.

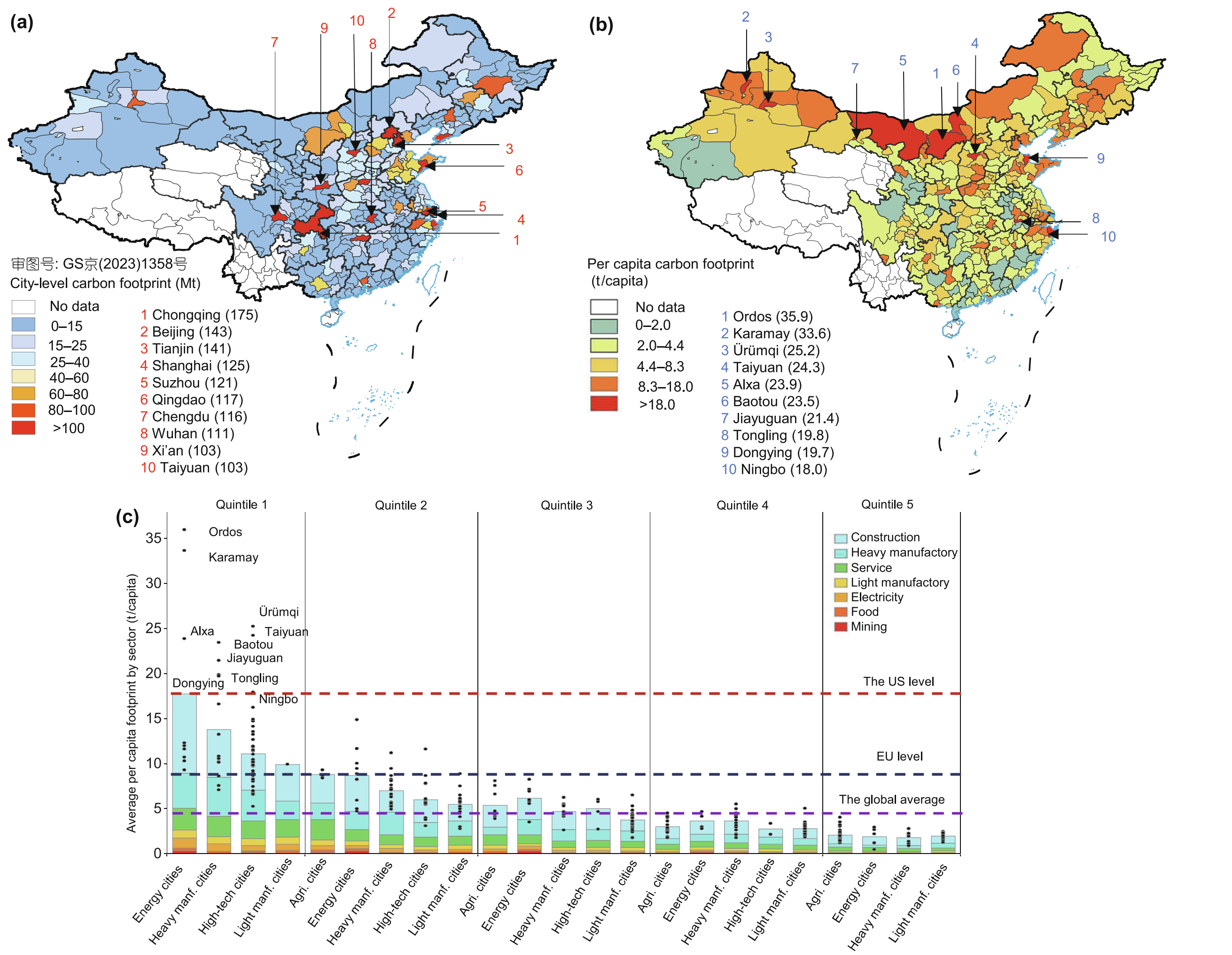

Fig. 1. Distribution and disparities in the carbon footprint of Chinese 309 cities. (a) The spatial distribution of carbon footprint for 309 cities; (b) the spatial distribution of per capita footprints for 309 cities; (c) the comparison of average per capita carbon footprints by quintile and by industry structure. The distribution of cities in each quintile can be found in the Supplementary materials (online). Note: service here includes high value-added sectors (e.g., finance) and low value-added sectors (e.g., transportation services).

Despite the large carbon flows generated between rich cities, less developed cities rely heavily on rich cities as a market, and also produce products and services for rich cities to sustain their economic growth (that is, value-added)—although at disproportionate environmental cost via greater carbon emissions. The economic growth of less affluent cities that is driven by rich cities is significant: 45% of the value-added of bottom quintile cities are generated through trade with top quintile cities. However, the inter-city supply chains show a cost-ineffective pattern which enlarges the disparity.

Fig. 2b shows the economic benefits adjusted by carbon costs between cities. Regarding emissions related to production for the richest cities (in million tonnes of CO_2), the bottom quintile cities get per emission value-added ranging from 3.6 to 8.4 billion Yuan, with cities reliant on agriculture—the main component of the bottom quintile cities (see Fig. S6 online)—only getting 5.7 billion Yuan. In contrast, the cities most reliant on high technology among the richest cities (which form the main percentage of top quintile cities) can generate 8.9 billion Yuan when trading with the least quintile cities. That pattern is also found in trade between the fourth and top quintiles, where high-tech cities of the richest group may get 9.4 billion Yuan from the trade, while fourth-quintile cities can only get at most, 7.7 billion Yuan.

Thus, rich cities that produce products with higher economic benefits (value-added) but lower environmental impacts can always profit from trade with less affluent cities, which produce products with high environmental impacts but lower economic benefits. The fragmentation of production may reinforce economic domination along the supply chains, as it is common to see low-value-added but high carbon-intensive industries transferred from rich cities to less affluent cities due to higher production costs in rich cities, like labour wage (transferring environmental costs), and host industries with high value-added and low carbon intensity (keeping economic benefits). Less developed cities may attain economic benefits and reduce the economic gap with rich cities, but higher environmental costs make the invisible disparity larger.

3.3. The leveraging opportunity of heterogeneous mitigation for super-emitting cities

The significant carbon inequality among cities indicates the leveraging opportunity that substantial mitigation can be achieved by a few rich super-emitters. The mitigation strategies of cities are varied depending on their position in the supply chains. Cities are categorised as net consumers, where their emissions embodied in exports are larger than those in imports; and as net producers if

(a) Cities where goods and services were consumed (columns); Cities where carbon emissions were generated (rows)

	Industrial structure	Q1	Q2	Q3	Q4	Q5	Carbon emissions generated
Q1	Agriculture	0%	0%	0%	0%	0%	
	Energy	2%	1%	1%	0%	0%	253
	Heavy manufactory	4%	1%	1%	1%	0%	415
	High-tech	10%	5%	4%	2%	2%	1241
	Light manufactory	0%	0%	0%	0%	0%	
Q2	Agriculture	0%	0%	0%	0%	0%	
	Energy	2%	1%	1%	0%	0%	256
	Heavy manufactory	4%	2%	2%	1%	1%	524
	High-tech	3%	1%	1%	1%	0%	279
	Light manufactory	2%	1%	1%	0%	0%	251
Q3	Agriculture	1%	0%	0%	0%	0%	
	Energy	3%	1%	1%	1%	0%	313
	Heavy manufactory	2%	1%	0%	0%	0%	203
	High-tech	1%	0%	0%	0%	0%	
	Light manufactory	3%	1%	1%	1%	0%	336
Q4	Agriculture	1%	1%	0%	0%	0%	
	Energy	0%	0%	0%	0%	0%	
	Heavy manufactory	3%	1%	1%	1%	0%	351
	High-tech	1%	0%	0%	0%	0%	
	Light manufactory	2%	1%	1%	0%	0%	223
Q5	Agriculture	2%	1%	1%	1%	0%	275
	Energy	0%	0%	0%	0%	0%	
	Heavy manufactory	1%	0%	0%	0%	0%	
	High-tech	0%	0%	0%	0%	0%	
	Light manufactory	1%	0%	0%	0%	0%	
	Carbon footprints (Mt)	2728	1085	910	607	389	

(b) Cities where goods and services were consumed (columns); Cities where economic benefits were recevied (rows)

	Industrial structure	Q1	Q2	Q3	Q4	Q5
Q1	Agriculture Energy	1.5	1.7	1.8	1.4	1.7
	Heavy manufactory	2.9	3.2	2.8	3.2	3.0
	High-tech	3.1	3.3	3.0	3.1	3.1
	Light manufactory	7.9	7.8	7.9	9.4	8.9
		2.6	2.6	2.5	2.5	2.4
Q2	Agriculture	3.8	4.0	4.4	4.5	4.2
	Energy	2.0	1.9	1.9	1.8	1.8
	Heavy manufactory	2.9	3.0	3.1	3.4	3.3
	High-tech	8.5	8.3	7.9	8.4	8.2
	Light manufactory	6.3	6.1	6.1	6.0	6.8
Q3	Agriculture	3.2	2.9	2.7	3.0	3.1
	Energy	2.1	2.1	2.2	2.0	1.9
	Heavy manufactory	4.0	5.0	4.2	4.6	4.3
	High-tech	7.6	7.2	7.4	7.5	8.1
	Light manufactory	6.5	7.0	7.0	8.1	8.1
Q4	Agriculture	5.9	5.6	5.6	6.0	6.4
	Energy	2.0	1.9	2.2	2.1	1.9
	Heavy manufactory	3.1	3.4	3.0	3.7	4.2
	High-tech	3.2	3.3	3.3	3.2	3.2
	Light manufactory	7.7	8.0	8.0	8.2	8.2
Q5	Agriculture	5.7	5.0	5.3	5.2	5.6
	Energy	5.3	5.1	4.6	5.4	4.5
	Heavy manufactory	3.6	4.2	4.0	4.3	4.8
	High-tech	5.8	5.1	5.2	5.4	6.7
	Light manufactory	8.4	7.5	8.1	8.4	6.8
	Value-added per unit of carbon emissions (billion Yuan/Mt)	116	115	114	121	121

Fig. 2. Inter-city carbon flows and disproportionality in economic benefits per unit of emissions. (a) Carbon flows between different cities by income quintile (Q1–Q5) and by industries (five categories). Q1 refers to the top-income cities and Q5 to the bottom-income cities. Numbers on the right refer to carbon flows generated from a type of city group; numbers on the bottom refer to total carbon flows driven by quintile cities. Note: the sum of all figures (%) is 100%. (b) The per unit of carbon emission economic benefits (value-added) acquired from the supply chains by cities.

the balance was reversed [27,61]. Net producer cities should adopt technology-based strategies (such as carbon capture and storage (CCS) technologies or applying ultra-low emissions standards for power plants) [62], while net consumer cities could call for demand-based efforts (such as improving energy efficiency in buildings or shifting to electric cars).

Fig. 3 identifies net producers and consumers among the 309 Chinese cities studied: 159 are net producers, and 150 net consumers. A leveraging opportunity for mitigation can be found with 32 super-emitters. Of the 32 super-emitters, 25 are from the top quintile, followed by 3 cities in the second quintile, 2 in the third quintile and 2 in the fourth quintile. The key super-emitters are responsible for 40% of the total carbon footprint (2909 Mt), of which 14 cities are categorised as net consumers with higher consumption-based emissions and should adopt demand-based strategies (type 1); and 9 are net producers with higher production-based emissions, and should follow technology-based strategies (type 2). The remaining nine cities have both high consumption-based and production-based emissions and need to adopt hybrid strategies that should involve both technological and demand-side solutions (type 3). However, it is important to note that type categorization is a fairly general method for selecting mitigation strategies. It may be more applicable to cities with notably high production or consumption-based emissions (32 super-emitters). For the majority of cities, however, additional information is required to tailor their specific mitigation pathways.

Super-emitters with high production-based emissions (18 cities with technology and hybrid strategies, or type 2 and type 3 cities) are centres of carbon-intensive manufacturing or energy production, which account for 27% of total carbon emissions. Fig. S7 (online) targets six key sectors that together account for 95% of the carbon emissions of super-emitters following technology-based strategies (type 3 cities), and 85% of emissions of super-emitters with hybrid strategies (type 2 cities). The electricity and the iron and steel sectors made the largest contribution, followed by petrol and coking products, coal products, non-metal products, and chemical products. The carbon intensities of the six key sectors in super-emitting cities with high production-based emissions are higher than the national average, indicating that technological solutions should be part of explicit mitigation targets [5].

For super-emitters using demand-based solutions (23 cities with demand-side and hybrid strategies, or type 1 and type 2 cities), the substantial potential for mitigation can be made by shifting the drivers of growth from investment to consumption. Urbanisation in China massively relies on large-scale infrastructure investments, but the pattern changed after the 2008 financial crisis, when drivers of urban growth began to gradually shift from investment to consumption [30]. At the national level, household consumption has overtaken investment and become the biggest contributor to economic growth since 2014. This shift has significant implications for mitigation, as household consumption demands fewer carbon-intensive products (e.g., cement, iron &

Fig. 3. Key carbon emitters and the emission composition. Consumption-based and production-based emissions for 309 cities by industry structure and quintile group. To implement the heterogeneous mitigation strategies, we categorise the super emitters into cities with demand-based mitigation (type 1), cities with hybrid mitigation (type 2), and cities with technology-based mitigation (type 3), according to their contribution to the carbon emissions (cities whose consumption-based or production-based emissions are >1% of total emissions).

steel) than capital investment (1.8 t/10^4 Yuan versus 1.1 t/10^4 Yuan).

Most type 1 and type 2 super-emitters are megacities with a high-tech industrial structure, including megacities such as Beijing, Shenzhen, and Shanghai. Nonetheless capital formation still takes a large proportion of their demands to maintain citizen's needs and economic growth. In China's megacities, about 55% of the city's total demands are from capital formation (Fig. S8 online). The figures for most developed cities are lower, with Beijing at 43%, Shanghai at 41%, Shenzhen at 42%, and Guangzhou at 44%. By contrast, the shares of global megacities are below 30%, ranging from 17% for Osaka to 27% for Seoul (due to data availability, we made comparisons with the five global megacities). That gap implies a mitigation opportunity arising from the ongoing economic transition of Chinese megacities.

Making the most of carbon inequality fosters a leveraged mitigation opportunity. Low carbon efforts of super emitters could make a substantial mitigation potential which creates extra carbon quota (or emissions space) to carbon peak, which can be freely allocated to less-developed cities for economic growth, via the collaborative mechanism (e.g., carbon trade scheme). Our strategy focuses on the mitigation of the rich super-emitters and allocates the carbon quota generated from the rich cities to the less affluent cities, which therefore can have carbon space to apply an investment-based strategy for their growth.

In the 18 cities of type 2 and 3, the potential carbon quota from technological mitigation is 459.9 Mt (6.3% of total carbon footprint) if reducing the carbon intensity of the six key sectors to the national average (technological light mitigation), and 1,019.5 Mt (14.1%) if reduced to the global average (technological deep mitigation). Regarding demand-side mitigation, we estimate that its potential for 23 types 1 and type 2 cities (demand-side light mitigation) can save a carbon quota of 384.3 Mt (5.3%). The quota can increase to 439.8 Mt (6.1%) if the investment-based growth pattern for all high-tech cities in the richest cities (top quintile) is shifted from an investment-driven growth pattern to the consumption-driven growth pattern. Fig. 4 shows that joint technical and demand-side mitigation can make carbon quota savings ranging from 844.2 Mt (or 0.84 Gt) to 1459.2 Mt (or 1.46 Gt). Projected by the China Academy of Engineering, China's carbon emissions are estimated to reach 12.2 Gt when achieving a carbon peak, and the existing carbon quota from 2012 is 3.2 Gt. Hence, the extra carbon quota created by mitigation efforts on 32 super emitters can increase by more than 30% of the current carbon quota from 3.2 to 4.7 Gt. The extra carbon quota saved by key super-emitters can offset the carbon deficit (443.9 Mt) generated from lifting the least affluent cities (123 cities, with a total population of 484 million) to the US$3600/cap (the average levels of quintile 3), or carbon deficit (1459.1 Mt) of lifting 185 cities (with a total population of 735 million) to $5300/cap (the average levels of

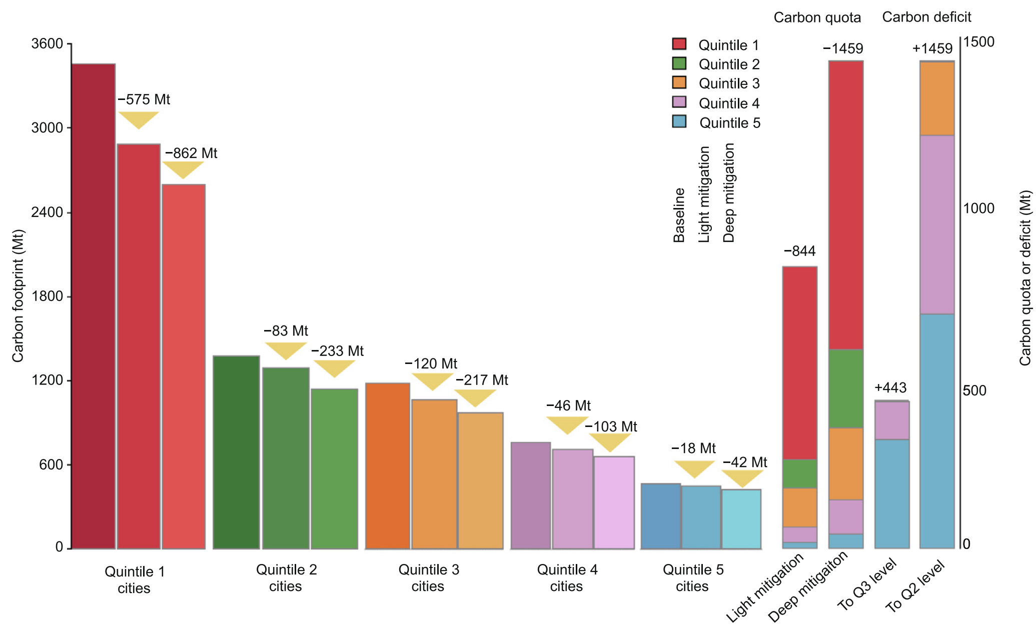

Fig. 4. Scenarios for carbon quota and the mitigations of technological solution and demand-side solution.

quintile 2). However, it is worth noting that the scenarios only reflect the mitigation targets for the grouped cities, but the specific approach to reach out to the target has to take more local details, such as nature endowment. For example, the technology-based approach to reduce carbon intensity can be achieved either by low-carbon technology (adopting the electric-arc furnace (EAF) instead of the widely used basic oxygen furnace in Tangshan's steelmakers) or green energy (promoting solar and wind energy in Ordos).

4. Discussion and conclusions

Our findings highlight a significant carbon inequality among Chinese cities, but it also highlights the leveraging opportunity that substantial mitigation offers if a few rich "super-emitter" cities are targeted. The carbon quota created by the key super emitters can be freely allocated to the less developed cities for their economic growth, which requires a collaborative mechanism such as a trade scheme. The results also show the importance of "proceeding toward peaking carbon emissions with a categorized, region-specific, orderly approach in phases" suggested in China's carbon peaking action plan. However, strategies adopted by key emitters need to be differentiated, based on their role in supply chains. Although direct mitigation via technological advances is more effective than indirect "demand-side" mitigation, technological solutions have limits, such as the surging marginal costs of promoting low-carbon technologies and energy transitions [63–65]. That has led to calls for more efforts towards demand-side mitigation in rich cities, such as shifts in development patterns (reducing carbon-intensive products used in investment) or building intelligent cities to improve energy efficiency by reducing traffic congestion, promoting green building, and encouraging electric cars [65,66]. For example, the better design in capital investment by using cross-laminated timber in construction in Nordic countries results in substantial carbon emissions reductions, which is one of the reasons for these countries with the least carbon intensity in capital formation [67,68].

Since the 2008 global financial crisis, China's urbanisation dramatically changed in the past decade, in which the driving factor of urbanisation of Chinese cities changed the most significantly. It is often formulated as the "New Normal" which refers to an economic engine transformation from heavily relying on large-scale investment and energy-intensive manufacturing into a new pattern led by high domestic consumption and value-added manufacture and services [30,69,70]. The economic transition has been well spotted after 2008, especially in 2012. The key feature is the rise of the Southwest and Central regions of China, therefore faster urbanisation in these regions, driving up supply chain-related emissions [71]. The recent policy agenda like "Dual Circulation" and "7 national metropolitan areas" reflects the requirement to prioritise domestic consumption and promote regional integration for development. Understanding the transition from investment to consumption and inter-city linkages can largely bridge the knowledge gap in the context of low-carbon initiatives and new development paradigms. Affluent cities previously powered by heavy investment and resource extraction are confronted with transition risks due to reducing capital investments, shutting down high-pollution manufactories, and limitation on resource extraction, which expects to decline their both production-based emissions and embodied footprints. However, it is notable that capital investment is crucial to economic growth. Such development pattern shifting is a progressive process with possibly adverse effects on the economy. Therefore, the transition should only be applied to the affluent developed cities, as we stated in our scenarios. The transition from investment to consumption may help reduce inter-city carbon flows, especially between affluent consumption megacities (e.g., Beijing and Shanghai) and industrialised cities (e.g., Tangshan). In our study, we showed the carbon emissions multiplier of consumption (carbon emissions embodied in supply chains per unit of spending for consumption purposes) is significantly smaller than capital investment, because fewer carbon-intensive products (e.g., iron and steel) would be used to produce items for household consumption [72].

China's low-carbon transition can thus achieve inclusivity by simultaneously tackling mitigation and equity. As we have seen, mitigation in rich cities provides a carbon quota for less affluent ones, thus enabling them to improve their living standards and economic growth, which inevitably involves higher emissions. The collaboration is built up on the inter-city supply chains.

However, the fragmentation of production among Chinese cities results in rich cities gaining higher economic benefits with fewer carbon costs than less affluent cities. A collaborative mitigation strategy rebalances benefits through the transfer of carbon credits gained in rich cities to poorer cities as carbon quotas. Therefore, mitigation in rich cities becomes even more crucial, not only due to their high carbon footprints but also because it directly determines how much carbon quota can be reallocated for poorer cities' economic growth [73]. Although the current carbon trade scheme in China is mainly based on infrastructures (e.g., power plants), the collaborative mechanism of carbon quota allocation can well equip with the carbon trade scheme which largely focuses on mitigation and reduction of carbon intensity, but is not designed for equity between cities. As suggested in our results, policymakers should take into account the gap among cities in the carbon quotation allocation. Large carbon quotations generated from rich cities could be freely allocated to poorer ones for development. A carbon trade scheme with the benchmark of carbon intensity may hardly benefit the poor cities which do not have carbon-intensive manufactures, as the revenue generated from carbon trade could be still mostly among richer cities. Therefore, fostering economic growth in less developed cities by allocating carbon quotas to poor cities is a crucial supplement to the current carbon trade scheme.

China's middle-income cities (quintile 2–quintile 4 cities) already have established industries such as heavy manufacturing and energy production, and their lower carbon transition prioritises the retrofitting policies targeting such sectors. Such policies would generate substantial economic or social costs, and undermine their development prospects and motivation [5]. They could, for instance, involve the substantial social costs of an industrial transition, such as the job losses of coal miners [74,75]. A compensation mechanism between rich super-emitters and middle-income cities is needed, following the "polluter pays" principle which puts the responsibility for compensation on the emitter [76]. Thus, cities with heavy manufacturing and energy production should be subsidised by those that benefit from the rich "downstream" cities on supply chains for whom they produce, and emit. That is feasible because a substantial share of rich cities' carbon footprints comes from middle-income cities. Mitigation in middle-income cities can thus help to reduce the carbon footprints of rich cities, and meanwhile add to the carbon quota for less affluent ones.

To implement the collaboration, the carbon quota saved by rich cities can be easily distributed to cities upstream if the allocation of the quota follows inter-city supply chains. For example, if poorer cities are more involved with rich cities through supply-chain activities, they should be allocated a higher carbon quota. This quote, as we have seen, is designed to offset carbon emissions generated by new infrastructure development and urbanisation. It is important to mention the "development cycle effect" where the evolution of cities has experienced several stages. It is historically evident that service or high-tech-based rich cities have experienced a rapid industrialising stage which invests heavily in carbon-intensive industries. But socioeconomic growth from such industrialisation and urbanisation then leads to the industrial transition, enabling a low-carbon service sector economy in the end. The collaboration mechanism can promote industrialisation in the least-income regions with carbon quota reallocation.

Given that China's poorest cities are also scattered through the country's most ecologically fragile regions (such as upstream of the Yangtze River), the industrialisation in these low-income regions should focus on green growth to optimise the use of carbon quota, rather than repeat the development cycle adopted by rich cities in the past, led by high-polluting, low value-added industries. Local industrialisation pathways could be designed to involve, for example, digital or renewable-energy industries, which have a relatively low environmental impact and high value-added [77–79]. For instance, establishing a big data centre in a remote location with abundant hydropower (such as Anshun, the lowest-income quintile city in southwest China) could make the most of renewable resources while creating employment opportunities [80]. Meanwhile, the investment in enabling the environment of these poor cities could be more crucial, as the low-carbon industry and technology are highly knowledge-based.

To promote collaborative inter-city offsetting, a mechanism for allocating carbon quotas that is both fair and efficient is required. Given that the right to emit is the right to develop, it is essential to build a national accounting system and ensure that the carbon quota may be given equitably to poor towns. The central government should be responsible for monitoring, verifying, and allocating carbon quotas to poor cities, while local governments can assign the quota to their essential industries. This allocation can include a performance-based method, such as a higher GDP growth with less carbon quota used. More carbon quotas could be allocated to cities with superior performance. Depending on the city's capabilities, this incentive could motivate local governments to optimise carbon quotas and promote the low-carbon transition. The carbon quota can be viewed as a supplement to China's emissions trading mechanism, which focuses solely on coal-fired power stations at this time. The quota supplied by prosperous cities should be allocated to other industries, such as steel and cement, which offer additional emissions space for their growth.

There are some limitations in our study. The method used in the paper (EEIO) is based on Leontief input-Output model, which has several assumptions. The model is a linear model based on the equilibrium; however, it is not always true in practice. The model assumes a fixed relationship between inputs and outputs or production recipes. Meanwhile, the sectoral resolution is blunt due to the data availability. The city-level MRIO table is with 42 aggregated sectors and cannot reflect cross-cutting activities or technology (e.g., chips). Over the past decade, the city's emissions experienced dramatic changes, with varying carbon trajectories across cities. Despite the data unavailability, we use production-based emissions for four representative cities to demonstrate the trend after 2012. For example, Shanghai (Q1 city) showed mitigation effects, where its carbon emissions slightly reduced by 1% from 2012 to 2019. The intensity reduction is the key contributor and reflects the mitigation efforts. However, other quintile cities found an increase in their carbon emission, such as Tangshan (Q2 city, from 280 to 413 Mt), Wenzhou (Q3, from 34 to 47 Mt), Xuzhou (Q4, from 100 to 128 Mt), and Xuancheng (Q5, from 11 to 18 Mt). These trends support the implications of our study, which identify opportunities for targeted mitigation efforts in the 32 super-emitting cities. Furthermore, recent trends help to validate the policy implications of our study. There are many factors related to their carbon trajectories, such as economic growth, population, supply chain characteristics (e.g., the evolution of industrial reallocation), and carbon intensity reduction. These factors changed massively over the period. For example, the economic growth for each city in the post-2012 was different. The economic growth of the cities in the southwest experienced a higher growth, while the cities in the northeast stagnated in terms of development. The industrial structure could be changed as well. Meanwhile, the mitigation policy and many significant historical events happened in the post-2012, such as the 2015 Paris Agreement or the 2018 trade war, which significantly affects these driving factors. Unfortunately, it is difficult to decompose the driving factors due to limited access to city-level data, and we will try to figure them out in our future work. But it is expected that the member cities of each quintile may change over the period. Therefore, the collaborative mechanism should be managed by the central government to identify the key super emitters. For example, the government could update the list of "aiding" cities (rich cities) and "aided" cities (poor cities).

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Heran Zheng led the study and drafted the manuscript with inputs from Yuli Shan, Jing Meng, and Dabo Guan. Heran Zheng, Zengkai Zhang,Yuli Shan, Daoping Wang, Li Li, Xiaoyu Liu, and Jiamin Ou prepared the data with inputs from Kuishuang Feng, Zengkai Zhang, Ya Zhou, and Li Li. Erik Dietzenbacher, Daniel Moran, Meng Jiang, Kuishuang Feng, and Johannes Többen advised the draft.

Data availability

The city-level MRIO table of 309 cities constructed in this study, and the city-level carbon inventory, can be accessed from the CEADs database (www.ceads.net). We publish the full result of our study in Supplementary materials (online). The data on global megacities mentioned in this study are derived from their input-output tables: Tokyo (https://www.toukei.metro.tokyo.lg.jp/sanren/sr-index.htm), Osaka (https://www.pref.osaka.lg.jp/toukei/sanren/index.html), London (https://www.london.gov.uk/business-and-economy-publications/london-input-output-tables), São Paulo (http://www.usp.br/nereus/?txtdiscussao=construcao-da-matriz-inter-regional-de-insumo-produto-para-o-brasil-uma-aplicacao-do-tupi), and Seoul (https://www.bok.or.kr/eng/bbs/E0000634/view.do?nttId=10059403&menuNo=400069&pageIndex=1).

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2023.08.016.

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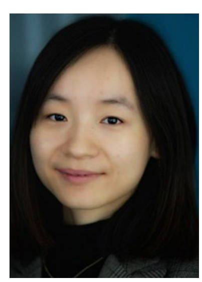

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