

## ARTICLE OPEN



# Urban metabolic flow in China's megacities doubled by material stock accumulation since the 21st century

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Buildings, infrastructure, and durable goods play a critical role in urbanization, akin to bones and muscles that structure the human body. These stocks contribute to the exploitation of over half of the world's resources and offer potential "urban mining" sources. However, the process of resource transformation regarding urban material stock growth and material flow alteration remains unclear. The metaphor of urban metabolism provides a new perspective to dissect this process, but current studies often spotlight only specific fragments, such as certain end-use types or materials. This study bridges this gap by establishing a comprehensive level-to-level analysis of urban "bone-muscle" metabolism in China's megacities. This study presents a comprehensive analysis of urban metabolism in China's megacities, tracking the lifecycle of material stock across over a hundred distinct end-use types and 12 categories of materials. Results indicate that annual metabolic flow in these cities has doubled since the early 21st century, reaching 264–737 Mt in 2018, with manufacturing, construction, and transportation as primary drivers. As accumulation intensifies, the material stock's growth rate diminishes logarithmically, hinting at increased efficiency and a move towards a steady state. Concurrently, scrap flow is on the rise. Driven by population growth, per capita scrap is projected to reach 2.0–4.7 t/cap by 2035, and material stock is expected to rise 1.4–2 fold. Proactive population planning and coordinated development strategies can mitigate the risks associated with this growth and maintain urban system stability.

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## INTRODUCTION

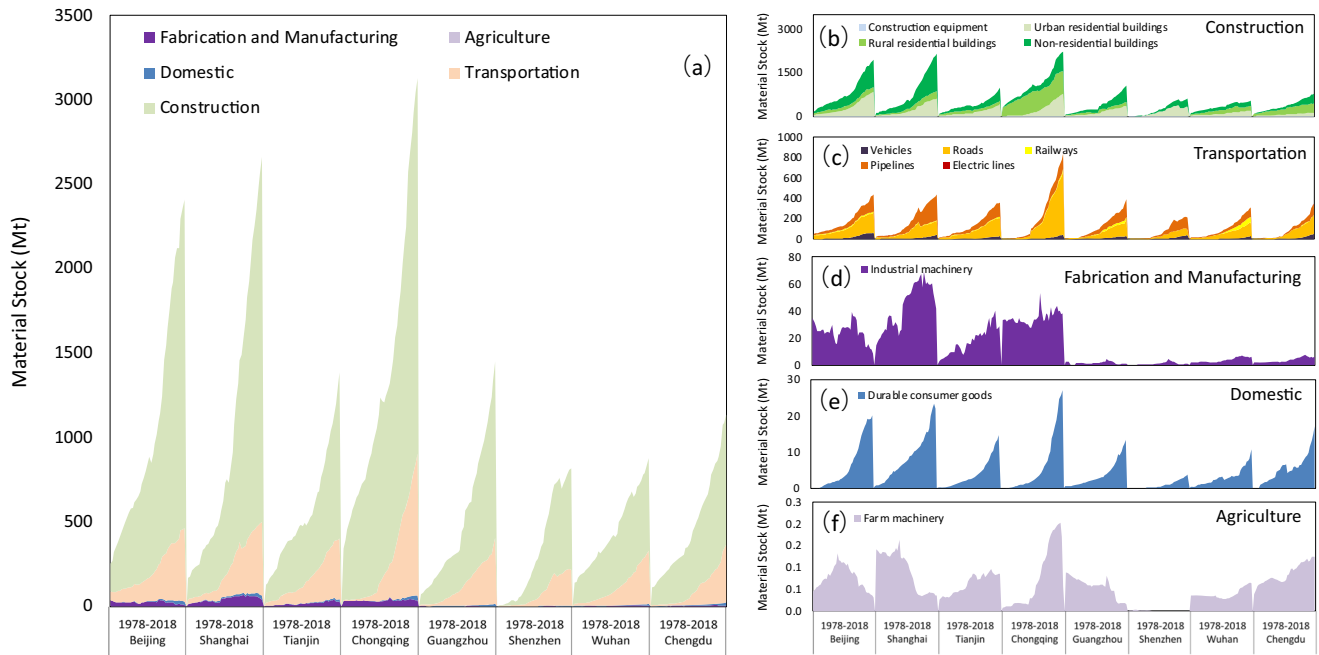
Drawing on the framework of urban metabolism, there is a metaphorical analogy where the roles of material stock, such as buildings, infrastructure, and durable goods, are similar to those of urban "bones and muscles". In the human body, bones and muscles are fundamental components that support and shape our physique. Similarly, the urban "bones and muscles" metaphor views material stock, such as buildings, infrastructure, and durable goods, as the city's "bones and muscles," forming the foundation that supports and shapes the city's form, influencing spatial layout, architectural styles, transportation networks, and industrial structures. They have long provided people with housing, transportation and communication services<sup>1,2</sup>. With the process of urbanization, they have gradually grown, simultaneously resulting in huge material consumption<sup>3–5</sup>. Urban "bone-muscle" metabolism is an important part of urban metabolism. Over half of the resources exploited globally are durable materials such as minerals. These are mined, processed, and used to produce, construct, maintain, or update the material stock of buildings, infrastructure, and durable goods, and they generate solid waste after reaching their lifespan. This process is called urban "bone-muscle" metabolism. The growth of urban "bones and muscles", i.e., the accumulation of material stock, is accompanied by "birth" and "aging", i.e., the addition of new products and scrapped products, "nutrient intake" and "excretion", i.e., material input and waste output. Refining the dynamic input and output "bones and muscles" metabolic process of materials, products, and sectors can distinguish the specific "bones and muscles" types of urban "birth" and "aging". This also helps locate the destination of "nutrient intake" and the source of "excretion". Facing urban issues like congestion, resource scarcity, and environmental pollution, this

can provide detailed and scientific support for finding the "disease focus" and diagnosing the "cause of the disease".

The unprecedented growth of the urban population has led to a substantial increase in the global demand for urban infrastructure and other stocks, seeing a rise of 23 times over the past 100 years. By 2050, 68% of the global population will live in cities, placing greater pressure on resources and the environment<sup>6–8</sup>. For a city to track the resources required to implement certain functions and identify the multiple environmental impacts of each product in the varied urban "bone-muscle" categories, it is necessary to analyze the material metabolic processes of input, output, transformation and circulation on an urban scale. By fully considering the various materials/products and waste/discharge involved in the urban "bone-muscle" system, one can establish an organic connection between the material stock function, its resource consumption, and environmental impacts. This aids decision-makers in tracing effects to their source.

The concept of urban metabolism can provide a new research perspective, frame of thinking, and guide for the identification and mitigation of resource utilization and emissions interactions between the natural environment and the social economic system<sup>9–11</sup>. Drawing from the concept of urban metabolism, scholars have undertaken beneficial studies across different scales, including cities<sup>12,13</sup>, urban agglomerations<sup>14</sup>, communities, and households<sup>15–17</sup>. Currently, the majority of urban metabolism research centers on the calculation and analysis of material flow, overlooking the escalating significance of material stock and not fully tapping into the essence of urban metabolism<sup>18</sup>. From the perspective of metabolism, scholars have established and developed the stock-flow cycle model for metallic elements<sup>19–29</sup> and extended it to nonmetals and biomass<sup>3–5,30–33</sup>. Most of these models are macro-accounting on a large-scale, whether on global

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**Fig. 1** Sectoral distribution characteristics of material stocks in China's megacities, 1978-2018. **a** Distribution in five sectors. **b** Changes in material stocks serving the construction sector. **c** The evolution of material stocks serving the transport sector. **d** The evolution of material stocks to serve processing manufacturing. **e** The evolution of the material stock that serves domestic consumption. **f** The evolution of material stocks to serve agriculture.

or national scales, either through horizontal (multi-study area comparison) or vertical (long-time series) observations of stock accumulation<sup>22,34–38</sup>, the cyclical state<sup>28,39–46</sup> and environmental effects<sup>3–5,47</sup>. These studies examined the metabolic flow or stock of specific substances or products without organically integrating the flow and stock. Therefore, they could focus on fragmented details and could not fully show the complete metabolic process. Using stock as the primary focus and analyzing its relationship with resource flow, environmental impacts, and services is crucial for tracking the evolution of urban ecological processes<sup>18</sup>. The resource flow contributes to the formation of stock, which in turn offers services and leads to environmental impacts. Resource consumption, environmental impact, stock formation, and service delivery all depend on the social sector in terms of the material and product flows<sup>48,49</sup>. This study comprehensively examines the level-to-level classification pedigree spanning materials, products (material stock), and sectors, vividly illustrating the entire process of urban “bone-muscle” metabolism.

The vast metabolic scale and prolonged lifecycle of megacities position them as iconic case studies<sup>50–52</sup>. Based on documentary provisions from China and the United Nations regarding megacities, and considering the geographical distribution, this study takes 8 Chinese megacities (Beijing, Shanghai, Tianjin, Chongqing, Guangzhou, Shenzhen, Wuhan, Chengdu) as representative examples (the basis for determining the scope of the study is detailed in Supplementary Methods). This study focuses on the metabolic flows related to buildings, infrastructure, and durable goods during the 21st century (2001–2018). Additionally, to calculate the waste flows, it is necessary to account for the accumulated historical stock. Therefore, the time range for the stock part goes back to 1978. A dynamic urban stock-flow network model was constructed to reflect the entire life cycle process of urban “bone-muscle” from “cradle to grave”. Concurrently, a detailed, high-resolution lineage spanning “material-product-sector-city” was established. The objective encompassed examining the external drivers and innate metabolic dynamics of urban “bone-muscle” growth, modeling future scenarios, and proffering

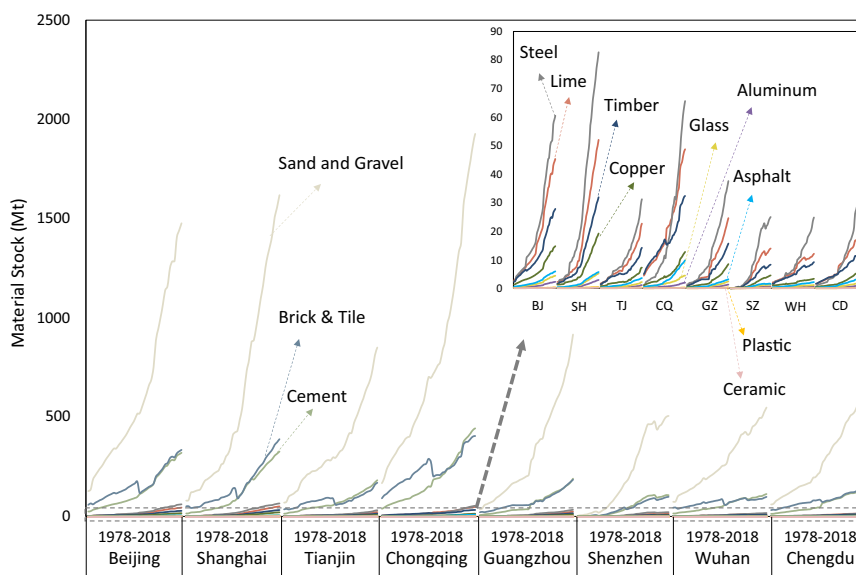
policy recommendations to bolster resource recycling and management in megacities and beyond.

## RESULTS AND DISCUSSION

### Material stock service pedigree

Over the past 40 years of reform and opening up, China's eight megacities have been growing and accumulating their material stocks rapidly, from <350 Mt to the magnitude of gigatons (811–3130 Mt). Buildings are the largest stock category in the 8 cities (74–85%), followed by infrastructure (11–21%) and durable goods (3–8%). Because of their differences in geographical condition, scale, and economic and social background, the amplification of material stock significantly ranges from 6-fold to 248-fold. Chongqing has the largest material stock scale due to its largest area and permanent population, while Shenzhen has the smallest scale but the largest growth, from a small fishing village into a megacity. Different categories of urban material stock are composed of different materials, and the same category of material stock could be formed by different substances in different geographical areas and serve different sectors, forming a diverse and multilevel service pedigree of “material-stock category-sector” (Fig. 1).

The construction sector is the largest stock service sector (approximately 80%), and its change has dominated the change in urban material stock, reaching 548–2224 Mt. The second is the transportation sector, which is smaller than the construction sector, for which Chongqing reached 840 Mt and other cities were all <1000 Mt. Fabrication and manufacturing, domestic consumption and agriculture all failed to exceed 100 Mt. Interestingly, the construction and domestic consumption sectors, which account for approximately 80% and 1% of the total material stock, respectively, have different orders of magnitude but similar trends, which may be because the stock sizes of the two sectors are closely related to the number of permanent residents. As urbanization intensifies, in the five highly urbanized cities of Beijing, Shanghai, Tianjin, Guangzhou, and Shenzhen, rural



**Fig. 2** Material stock in terms of 12 types of building materials.

residential buildings have gradually been replaced by urban residential and non-residential buildings, with the share of rural residential buildings not exceeding 18%. Roads and pipelines, which serve the transportation sector, are the two most important types of infrastructure, accounting for 48–76% and 23–49% of the total infrastructure, respectively. Roads, as the most basic travel facilities, are being laid at an accelerated pace in major cities. Water, gas, and other basic living materials are delivered to thousands of households through urban water supply, drainage, gas, and other pipelines. With the improvement of roads, vehicles serving the transportation sector gradually replaced industrial equipment serving the fabrication and manufacturing sector to become the largest subcategory of durable goods stock. The demand for transportation in megacities has an annual growth rate of 12–38%, while the fabrication and manufacturing sectors have gradually developed into high-end and sophisticated industries, showing a shrinking volume or slow growth, with an annual change rate of –3% to 6%.

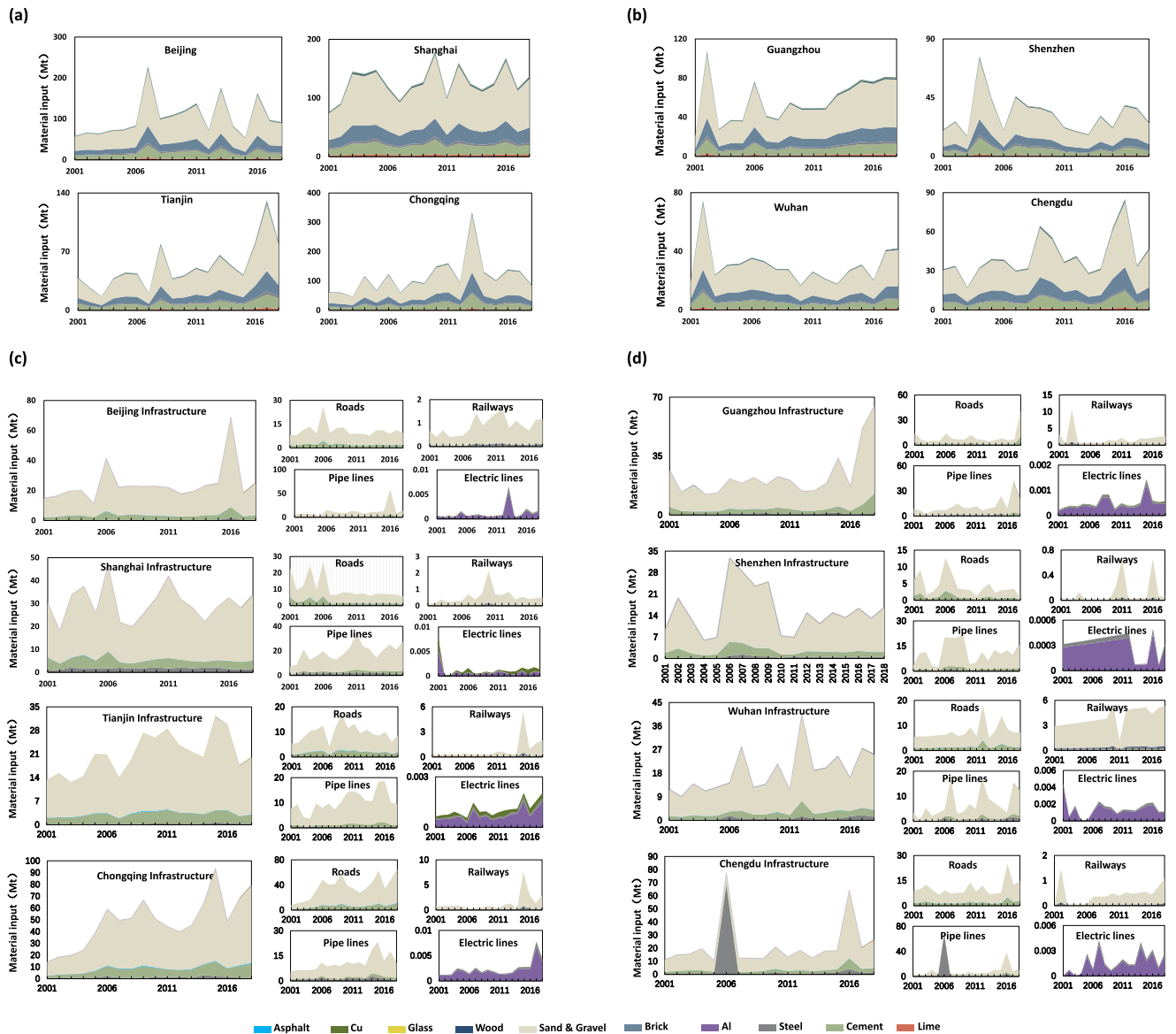
In terms of the stock category of material services, the service pedigrees of sand and gravel, and cement are relatively broad, while the distributions of brick and tile, copper, aluminum, and steel are relatively concentrated, basically serving buildings (See Supplementary Fig. 1 and 2). As the “cornerstone” of the built environment, the consumption of sand and gravel increased by more than 8 times during the study period (Fig. 2), and its share increased from over 50% in 1978 to approximately 65% at the end of the study (See Supplementary Fig. 3). Cement, as an important witness to the process of urbanization, increased its share of consumption from approximately 11% to approximately 14%. After 2000, the consumption of cement approached or even exceeded that of brick and tile. These changes are mainly reflected in the reduction of the share of services for rural residential buildings and the increase in the share for the other two types of buildings, pipelines, and roads (see Supplementary Figure 1). Steel, as the most important metal building material, steel increased by approximately 32 times during the study period, and its share of use increased from 0.4–2.1% to 2.2–3.3%. Mainly serving non-residential buildings (22–44%) and urban residential buildings (13–45%), the share of Chengdu and Wuhan steel used for pipelines increased significantly, from 24% and 14% to 46% and 39%, respectively. The share of copper and aluminum in use is approximately 1% and less than 0.1%, respectively, and the majority is used in non-residential buildings (45–90%). Bitumen

and plastic, the two types of fossil materials, did not reach 1% of the total amount (2–10 Mt), with the proportion of plastic being 0.04%, but with the rapid expansion of building and pipeline construction (increasing by at least 15 times), it cannot be ignored in future stock management.

#### Resource transformation process driven by urban “bone-muscle” growth

The annual growth of urban stock is derived from the conversion of material flows. A megacity in China inputs between 49–171 Mt of new stock per year. Approximately 62–81% of the material input goes into the building (Fig. 3a), with sand and gravel showing the most demand (60–61%), followed by brick and tile (17–19%), cement (13–15%), and steel (2–3%). Shanghai has the highest annual input of materials into buildings (127 Mt), while Chongqing (115 Mt) and Beijing (103 Mt) also exceed 100 Mt. Infrastructure requires fewer materials than buildings. Even though the subcategories of infrastructure are more diverse, their material compositions are notably heterogeneous. Among the materials input into infrastructure (Fig. 3b), sand and gravel amount to 67–85%, and cement comprises 11–15%. Chongqing’s infrastructure requires the largest amount of material per year (49 Mt), mostly sand and gravel used for road and pipeline construction. The proportion of steel varies the most among cities (1–21%). This disparity largely stems from variations among cities, especially concerning railways and gas supply pipelines. These two types of infrastructure require a large amount of steel consumption. Chengdu has a large distribution, with an annual increase of 4.6 Mt, while Tianjin has a relatively small distribution, with only 0.3 Mt. Approximately 6% (2 Mt) of Shanghai’s annual input material is steel, and nearly 90% is used for gas (natural gas) and water supply lines.

The conversion of urban stock into flow manifests when the product reaches the end of its service life, resulting in scrap flow. The annual scrap of 8 megacities is significantly smaller than the new stock, ranging from 14–67 Mt, which is less than half of the material inflow (Fig. 4). The 8 megacities are still in the stage of strong demand for new stock input, with an evident lag in scrap flow. Since the turn of the century, Chongqing’s scrap flow (67 Mt) has surpassed that of Shanghai (49 Mt) and Beijing (47 Mt), leading other cities by a significant margin. The demolition of non-residential buildings (17–35%) and rural residential buildings (15–49%, excluding Shenzhen) is the main source of the waste

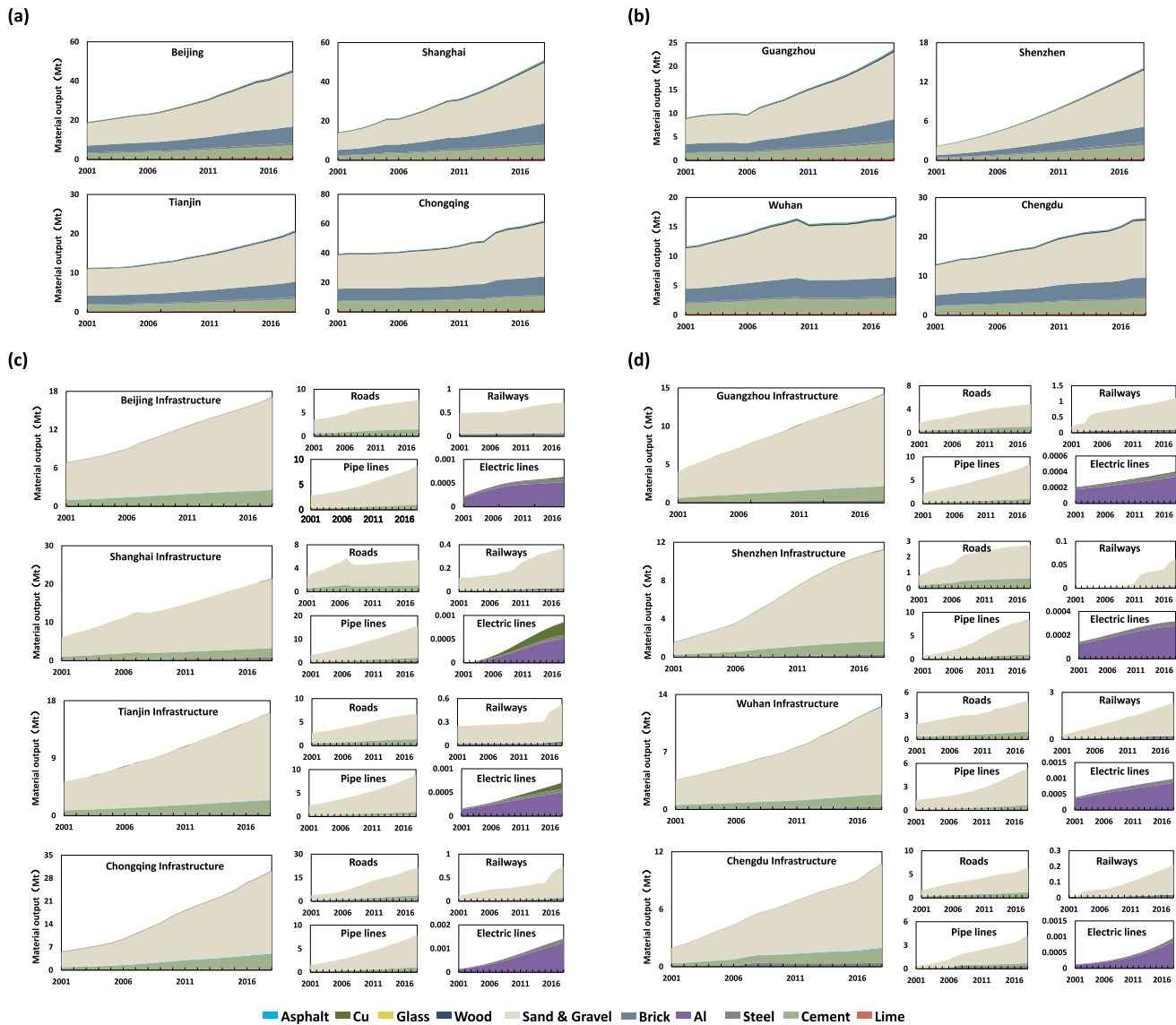


**Fig. 3** Annual material composition of materials inflow in China's megacities, 2001–2018. **a** Building: Beijing, Shanghai, Tianjin, Chongqing. **b** Building: Guangzhou, Shenzhen, Wuhan, Chengdu. **c** Infrastructure: Beijing, Shanghai, Tianjin, Chongqing. **d** Infrastructure: Guangzhou, Shenzhen, Wuhan, Chengdu.

stream, followed by pipelines (7–28%), roads (10–17%) and urban residential buildings (6–24%). Buildings contribute to 54–75% of the total built environmental waste, which is slightly less than their resource input proportion (62–81%). This is mainly because the average lifespan of buildings (25 years) is typically longer than that of infrastructure (21 years). Approximately 10–41 Mt of sand and gravel waste is produced in the built environment of megacities every year, which is approximately 2 times that of all other wastes. Annually, 0.4–1.2 Mt of steel waste, 0.2–1.1 Mt of copper waste, and 0.03–0.2 Mt of aluminum waste are produced. Compared with nonmetallic waste, the amount of metal waste is smaller, but the recycling value is higher. Although the outflow of asphalt and plastic waste is no more than 0.3 Mt per year, their environmental impact is considerable. For example, plastics, although used in a small amount, account for 8% of global carbon emissions from construction activities<sup>53</sup>. Megacities produce a variety of wastes, which should be comprehensively considered in terms of the volume, recycling value, and environmental impact.

The size and growth status of urban “bone-muscle” structure directly influence the amount of material they require and the waste they produce. The analysis of how material stock drives flow across 8 cities reveals an intriguing pattern. There is a natural logarithm function relationship ( $R^2 = 0.6541$ ) between the new stock and the accumulation of material stock; that is, with the accumulation of material stock, the new stock keeps rising (Fig. 5a), but the growth rate is slowing down, indicating that the efficiency of the stock consumption flow is constantly improving, and the city tends to steady state. There is a linear relationship between the scrap amount and material stock accumulation, with a positive correlation ( $R^2 = 0.9558$ ); that is, the larger the accumulated stock is, the larger the scrap amount will be (Fig. 5b). When the material stock increases by 1 Mt, approximately 0.03 Mt of scrap flows will be generated, which is consistent with Han et al.<sup>54</sup> and Dai et al.<sup>55</sup> (The detailed data are listed in Supplementary Methods). Considering the differences among the 8 cities, this study further explored whether the impact of the size of the material stock in each city on the increase and





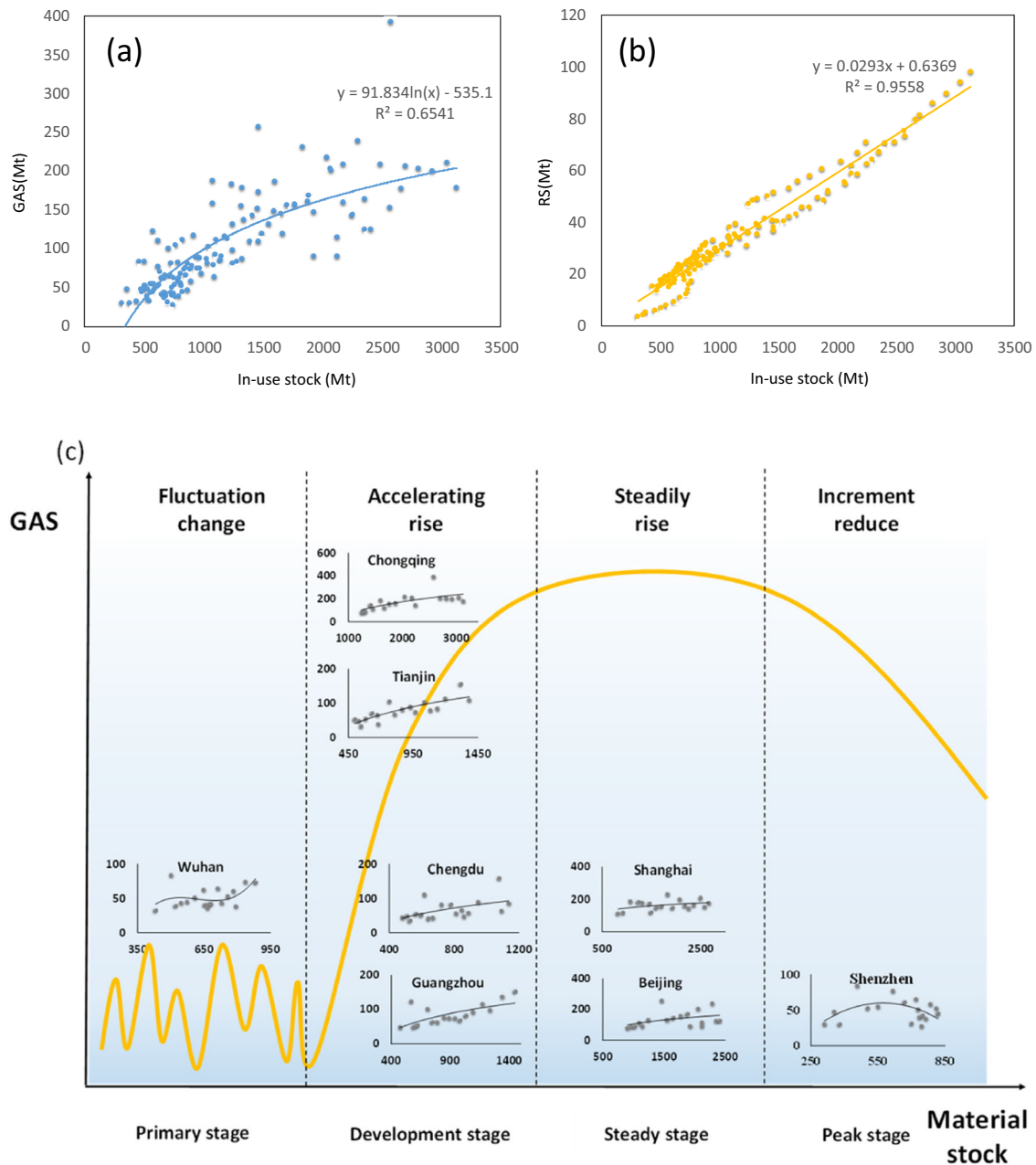
**Fig. 4 Annual waste material composition in China's megacities, 2001-2018. a** Building: Beijing, Shanghai, Tianjin, Chongqing. **b** Building: Guangzhou, Shenzhen, Wuhan, Chengdu. **c** Infrastructure: Beijing, Shanghai, Tianjin, Chongqing. **d** Infrastructure: Guangzhou, Shenzhen, Wuhan, Chengdu.

decrease conforms to the above rules (See Supplementary Fig. 4a, b). The relationship between the scrap amount and material stock accumulation showed a consistent linear growth relationship in the 8 cities. The relationship between new stock and the accumulation of material stock is different. According to the situation of 8 cities, it can be divided into four stages, namely, the primary stage, development stage, steady stage, and peak stage (Fig. 5c). When it is in the primary stage of stock accumulation, the change in newly added stock fluctuates relatively. Wuhan is a representative city in the primary stage because of its small scale of material stock. In the development stage, the new stock increases rapidly with the accumulation of stock, and representative cities are Guangzhou and Tianjin. After the accelerated accumulation, a city may enter the steady stage. At this stage, with the further accumulation of the stock, the newly added stock is relatively stable, which can be represented by the city of Shanghai. Finally, the accumulation of stock may enter the peak stage, when the accumulation of material stock tends to be saturated and the new stock will be reduced. Shenzhen is the only city among the 8

cities that has entered this stage. Thoroughly considering the inherent growth rules, which are informed by the similarities and differences of the 8 cities, aids in understanding a city's current stage. Judging the size of the stock solely is challenging, and growth can often be inconsistent with the accumulation stage of the stock. For example, Shenzhen has the smallest stock scale, but based on the relationship between the increment and the stock, Shenzhen has entered a relatively mature peak stage.

#### Tracking the urban "bone-muscle" metabolic network

Stock-flow transformation is an important link in the urban metabolic network. By mapping the input, output, and transformation processes of materials of different stock categories into the metabolic network on the scale of sectors, it can be found that more than 95% of the stock-flow transformation occurs in the construction and transportation sectors, and the transformation amount of the fabrication & manufacturing sector is no more than 4% annually. The conversion of domestic consumption and the



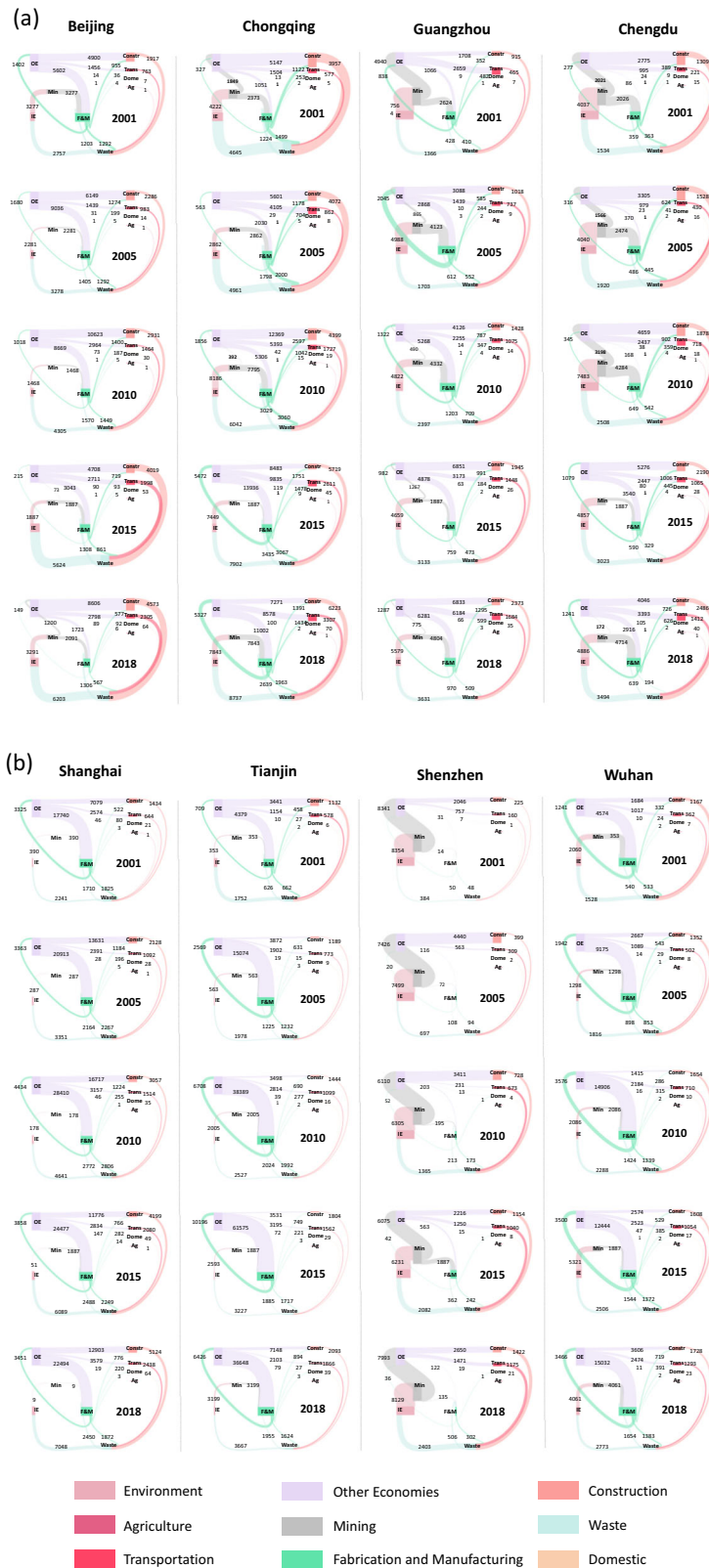
**Fig. 5 Relationship between material stock and flow in China's megacities. a** Relationship between material stock and GAS. **b** Relationship between material stock and RS. **c** A sketch map of the four stages.

agricultural sector is less than 1% a year (See Supplementary Fig. 5).

Further tracking the whole process of urban “bone-muscle” metabolism from cradle to grave in China's megacities, the network metabolic flow increased 2-fold from 156–401 Mt in 2001 with an average annual growth rate of 1–9% to 264–737 Mt in 2018 (see Supplementary Table 8). The pattern of the network presents certain differentiation. The metabolic network pattern of Beijing, Chongqing, Guangzhou, and Chengdu is relatively dispersed (Fig. 6a), mainly distributed in 7 sectors (except agriculture and domestic consumption). In Chongqing, Guangzhou and Chengdu, the network pattern distribution is more homogeneous. The construction sector in Beijing has replaced the fabrication and manufacturing sector, and its position in the network is becoming increasingly prominent. By the end of the study, 65% went to the construction sector. The network pattern

of the other 4 cities is more concentrated, with the metabolic flow clustered in 1/4 to 1/3 of the sectors (Fig. 6b). The metabolic network flow in cities like Shanghai, Tianjin, and Wuhan is primarily concentrated in the fabrication & manufacturing sectors, along with other economic sector. The flow from other economies to the fabrication and manufacturing sectors contributes 27–65% of the metabolic flow in the network. The metabolic flow in Shenzhen is concentrated in other economies, the environment, and mining sectors, and the flows between the three sectors reach 53–82% of the total flow of the system.

The study identified general commonalities in the changes in metabolic pathways across 8 cities (See Supplementary Table 11). Flow exported from other economies predominate the network, accounting for approximately 21–66% of the total. Notably, there's a growing reliance on external imports or transfers, with an increase ranging from 1/10 to 4 times. Among these flows, the



**Fig. 6** Dynamic change in the metabolic network in China's megacities. **a** Beijing, Chongqing, Guangzhou, and Chengdu. **b** Shanghai, Tianjin, Shenzhen, and Wuhan.

resources imported or transferred to the construction sector and transportation sector showed an increasing trend in all 8 cities. In addition, the materials inputted from the local fabrication and manufacturing sector to these two sectors have generally been on

the rise, indicating that the material demand for the infrastructure construction of China's megacities increased significantly (the construction and transportation sectors increased 38% to 3 times and 43% to 5 times, respectively). The overall end-of-life flow is

also increasing (1–6 times), mainly from manufacturing, construction, transportation, and domestic consumption. Although the amount of recycling is increasing (1/10–9 times), the final emissions are still significant (increased 1–5 times). Regarding the export or transfer of minerals, mainly from the mining sector, and industrial products from the fabrication and manufacturing sector, on the whole, the former shows a decrease (–1% to –100%), while the latter increased (4% to 15 times), indicating that the output of megacities is no longer dependent on environmentally damaging mining minerals but mainly on fabrication and manufacturing products.

### Robustness of the metabolic system

The evaluation of the metabolic network's robustness shows that Shanghai performs the best, and the robustness index value largely aligns with the vitality/survival window (approximately 0.37), which means that the efficiency and diversity of the system reach an ideal balance and there is neither undue pressure from high efficiency nor inefficiency from too much redundancy (Fig. 7). The system robustness indices of Beijing, Tianjin, Wuhan, Guangzhou and Chongqing are slightly skewed to the right in the figure (0.31–0.37). The former two indicators mainly show a decrease, and the latter are gradually improving, while Wuhan is relatively stable (0.33–0.36). The construction sector in Beijing is dominant, followed by the fabrication and manufacturing sector, and the remaining sectors are relatively balanced. With the contraction of the processing manufacturing sector, the degree of order is relatively high (up to 0.57 in 2018), and the volatility of the system robustness decreased to 0.32. From 2008 to 2015, the advantages of the fabrication and manufacturing sector in Tianjin continued to expand far more than other sectors, and the diversity of the system declined, which resulted in the robustness of the system decreasing from 0.37 to 0.34. In 2004, Wuhan showed a significant decline in the robustness of the system (0.33), mainly because the advantage of the mining sector was too large in that year, resulting in the degree of order reaching 0.54, exceeding the ideal equilibrium state. From 2002 to 2006 and 2002 to 2005, the robustness of Guangzhou and Chongqing increased from 0.31 to 0.35, and the degree of order recovered from 0.58 and 0.59 to 0.48 and 0.49, respectively, moving toward the ideal equilibrium of the system. During this period, the redundancy (diversity) in the metabolic systems of both cities increased, and the development of various sectors was more balanced. The redundancy of the metabolic system in Chengdu increased gradually, and the robustness improved, increasing from 0.22 in 2004 to 0.32 in 2018. The robustness index of Shenzhen is significantly skewed to the right (0.17 in 2018), and the import and export or transfer flows are large. Other economies have excessive advantages in the system, and the system efficiency is high, but the diversity is unsatisfactory.

### Future scenarios

The growth of urban "bone-muscle" is affected by multiple factors. Considering the comprehensive development status of megacities, population was taken as the key driving factor of scenario simulation (see Supplementary Discussion for details). The results show that by 2035, the material stock scale of Chongqing will still be the largest of the 8 cities ( $\geq 4737$  Mt), and the difference between Chongqing and the other 7 cities becomes more pronounced (Fig. 8). In the baseline scenario and scenario B (United Nations forecast scenario), the material stock scale of Beijing and Shanghai will reach more than 3000 Mt by 2035, while in scenario A (policy planning scenario), it will not reach 2400 Mt. This shows that Beijing and Shanghai can restrain the accelerated accumulation of stock by effectively and reasonably controlling the population growth under the policy planning scenario. By 2035, the 8 cities will maintain the highest proportion of material

stock serving the construction sector (62%), second only to the transportation sector (17–36%). In short, medium, and long-term projections, scenario A is the optimal short-term scenario for Beijing and Shanghai. In the short-term, it's best to control population growth and restrain stock growth through policies. The newly added stock in scenario B showed a downward trend. In the medium- and long-term time series, scenario B should be prioritized to reduce the metabolic scale of megacities and the pressure on resources and the environment. However, under scenario A, the system is more robust, indicating that in a longer-term perspective, the development in accordance with the policy planning objectives will help these cities to maintain the robust state of the urban system (see Supplementary Discussion for details).

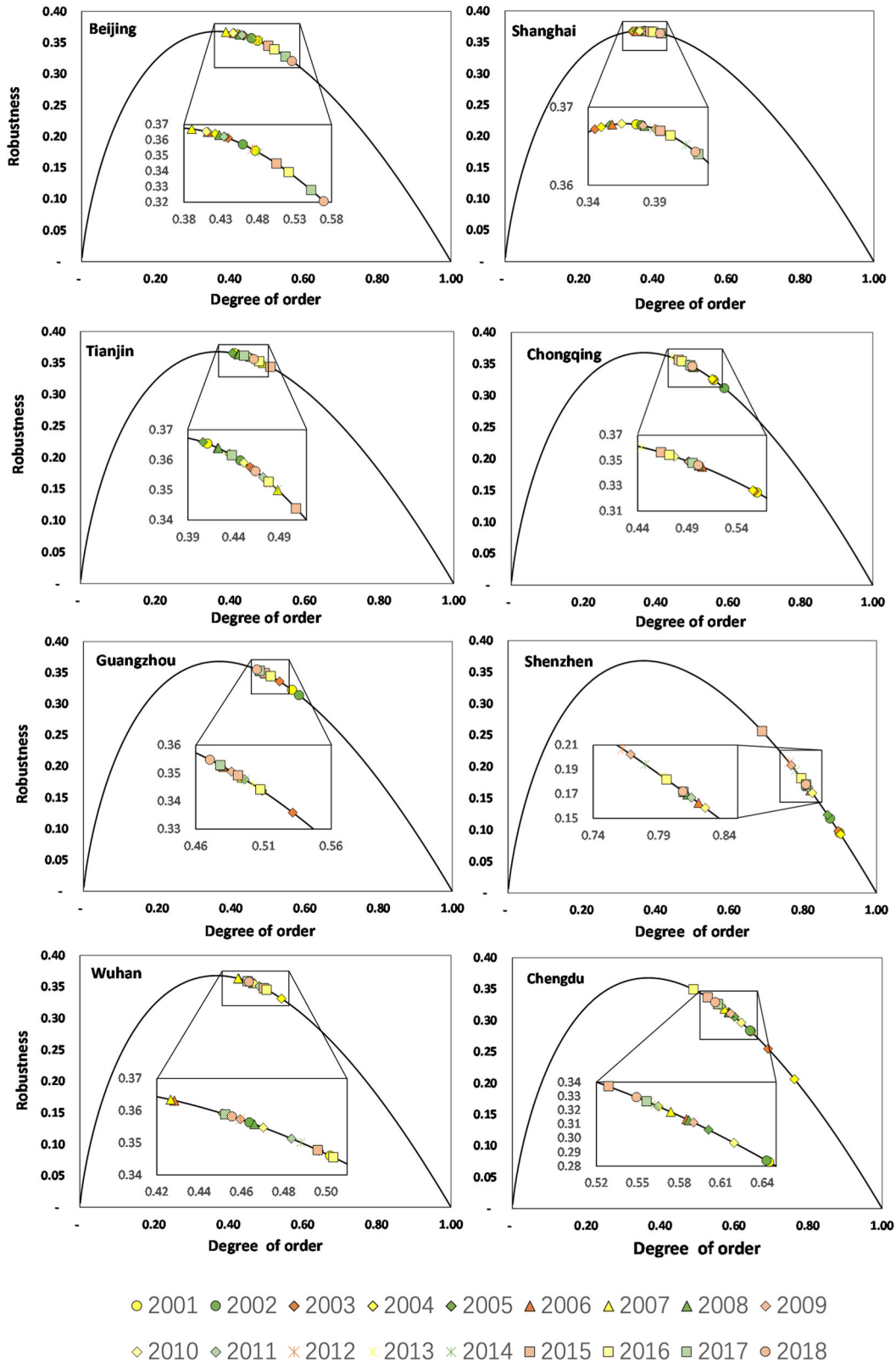
### Policy suggestions

*Improve the level and efficiency of stock service and utilize the stock service opportunities fairly.* There are differences in the capacity and level of stock service in China's megacities, so adopting the goal of stock service equity can promote the flow of resource factors. The difference in per capita consumption of the same resource between cities is 1.6–3.0 times, while the difference in in-use density between cities is even larger, reaching 13–52 times (see Supplementary Discussion for details). Cities at different stages of development (the primary stage, development stage, steady stage, and peak stage) should implement varied resource management strategies.

For cities in the primary and development stages, which also have a lower degree of urbanization and weak stock service capabilities (such as Chongqing, Chengdu, and Wuhan), the focus should be on attracting investment and developing local industries, while implementing sustainable urban planning to mitigate overcrowding and resource overuse. It is noteworthy that these cities have a built environment density of less than  $10 \times 10^4 \text{ t km}^{-2}$ , with sparse or uneven distribution and low stock accessibility. Therefore, in the future, efforts should be made to strengthen the construction of convenient urban communities, rationalize the layout of urban functional areas, optimize land use, and reduce resource wastage and environmental pollution. Initiatives like the "15-minute community living circles" and other sustainable environments can enhance their stock service capacity. Besides, Chongqing and Chengdu serve as central cities in the Chengyu urban agglomeration. In the future, leveraging Chongqing's infrastructure, especially road stock advantages, should drive stock accumulation in other areas, significantly improving infrastructure connectivity and establishing a western comprehensive transportation hub. This will contribute to the co-construction of the "Belt and Road" initiative and promote green development in the Yangtze River Economic Belt. Wuhan, with the highest proportion of railway stock among the 8 cities, is closely related to its core location in the middle reaches of the Yangtze River and its connection to the east-west transportation hub. Wuhan should leverage its vital status in transportation and logistics to promote the development of the Wuhan metropolitan area, and drive integrated development in the middle reaches of the Yangtze River city cluster.

For cities in the steady and peak stages that have a high degree of urbanization and strong stock service capabilities (such as Shenzhen, Shanghai, and Beijing), they should focus on maintaining and enhancing existing infrastructure. Notably, the built environment densities of Shenzhen and Shanghai are  $69 \times 10^4 \text{ t km}^{-2}$  and  $40 \times 10^4 \text{ t km}^{-2}$ , respectively. Additionally, the per capita stock of Beijing is  $111 \text{ t cap}^{-1}$ , nearly twice that of Chengdu. This indicates that residents in these cities enjoy relatively more opportunities for stock, complete urban construction, and rich public service resources. However, it also implies more resource factors are concentrated in these key cities.





**Fig. 7** Robustness evaluation of the metabolic system in China's megacities, 2001-2018.

Therefore, these cities should implement effective resource management policies, such as recycling plans and waste management policies, to deal with the linear growth of solid waste caused by the accumulation of stocks. Shenzhen and Shanghai, as central cities in the Greater Bay Area and the Yangtze River Delta

Economic Zone, are vital customs ports and logistics hubs. Their demand for non-residential buildings, such as commercial and trade, and warehousing spaces, continues to expand, resulting in a substantial conversion of resources stored in buildings. These cities also have advantages in comprehensive transportation hubs,

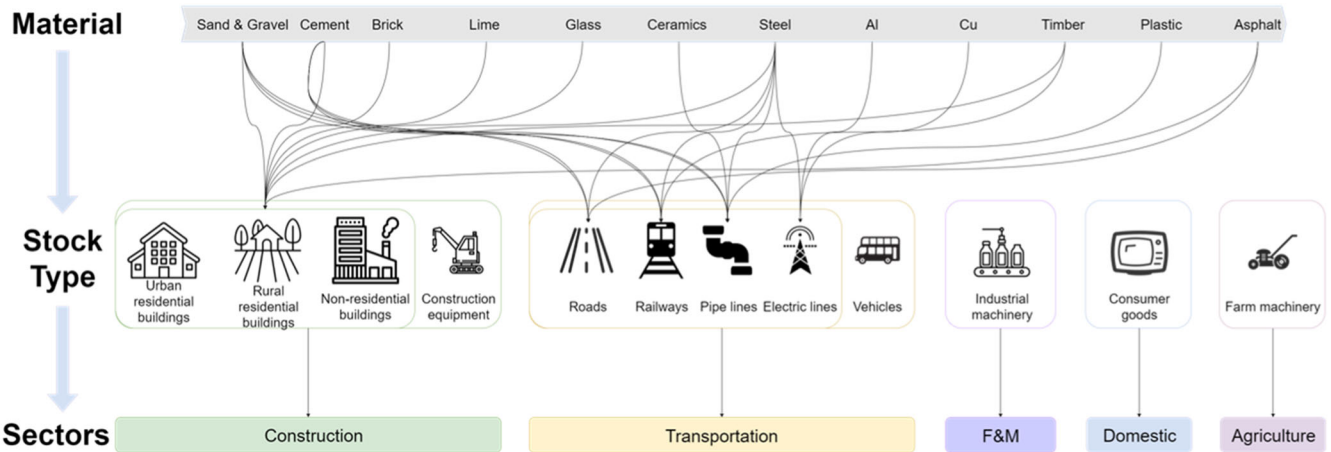
City	Indicators	2018	2025			2030			2035		
			BAU	Scenario A	Scenario B	BAU	Scenario A	Scenario B	BAU	Scenario A	Scenario B
Beijing	P (per ten thousand person)	2154	2474	2213	2481	2731	2256	2666	3015	2300	2785
	Stock (Mt)	2408	2610	2227	2621	2989	2290	2893	3406	2354	3068
	GAS (Mt)	125	143	74	138	161	76	126	180	78	98
	RS (Mt)	71	72	62	72	82	63	80	93	65	84
Shanghai	P (per ten thousand person)	2424	2646	2455	2888	2817	2477	3114	2999	2500	3254
	Stock (Mt)	2659	2606	2287	3011	2892	2325	3389	3196	2363	3622
	GAS (Mt)	177	129	72	184	141	73	160	154	74	125
	RS (Mt)	80	74	65	86	83	66	98	92	67	105
Tianjin	P (per ten thousand person)	1560	1903	1728	1735	2193	1859	1858	2528	2000	1941
	Stock (Mt)	1384	1656	1436	1445	2023	1601	1600	2445	1779	1704
	GAS (Mt)	109	116	75	78	137	82	75	160	89	67
	RS (Mt)	42	49	43	43	59	48	48	71	53	51
Chongqing	P (per ten thousand person)	3102	3300	3221	3268	3449	3309	3334	3606	3400	3371
	Stock (Mt)	3130	4337	3894	4155	5176	4390	4526	6054	4898	4737
	GAS (Mt)	179	289	211	224	318	227	188	348	242	169
	RS (Mt)	98	125	114	120	147	126	130	169	140	135
Guangzhou	P (per ten thousand person)	1490	1959	1682	1755	2381	1834	1890	2894	2000	1974
	Stock (Mt)	1451	1826	1499	1585	2325	1679	1744	2933	1875	1844
	GAS (Mt)	152	142	78	87	176	86	78	218	96	70
	RS (Mt)	41	54	44	46	69	49	51	87	55	54
Shenzhen	P (per ten thousand person)	1303	1622	1522	1482	1896	1700	1590	2217	1900	1661
	Stock (Mt)	819	1062	991	963	1254	1117	1040	1479	1257	1089
	GAS (Mt)	45	67	53	46	81	61	44	98	70	41
	RS (Mt)	27	32	29	28	40	35	31	50	40	33
Wuhan	P (per ten thousand person)	1108	1286	1309	1218	1431	1474	1303	1592	1660	1360
	Stock (Mt)	882	1095	1124	1005	1285	1342	1116	1496	1586	1192
	GAS (Mt)	73	75	81	60	86	94	60	99	109	55
	RS (Mt)	31	39	40	36	47	49	40	55	58	43
Chengdu	P (per ten thousand person)	1633	1953	1880	1853	2219	2080	1988	2522	2300	2076
	Stock (Mt)	1136	1485	1399	1366	1802	1636	1527	2162	1898	1632
	GAS (Mt)	85	111	94	86	130	107	81	152	121	74
	RS (Mt)	40	52	49	48	63	58	54	76	67	57

**Fig. 8** The metabolic index value of urban “bone-muscle” in short, medium, and long-term projections of China’s megacities under three scenarios.

with high stock accumulation in roads and railways. These “bone-muscle” development advantages lay the foundation for constructing international trade centers and providing a conducive environment for the rapid growth of supply chain enterprises. In the future, Shenzhen, and Shanghai should maintain their advantages in high stock output rates, strengthen the commercial and transportation hub layout, and play essential roles in guiding China’s transformation towards the high-end of the global value chain. Notably, the transition in Beijing’s metabolism network from manufacturing to the construction sector reflects the strategic execution of Jing-Jin-Ji regional coordinated development and the shift of non-capital functions. In the future, deeper cooperation in industrial division within the Jing-Jin-Ji region should be pursued, clearly defining key areas, suitable regions, and operational paths for industrial transfer and undertaking, establishing a comprehensive regional industrial chain system, and boosting resource flow through industrial collaboration.”

*Improve the metabolic quality of urban “bone-muscle” and promote green development in the future.* Megacities, especially high-density areas like Shenzhen and Shanghai, harbor abundant potential “urban minerals” within their limited urban space.

Recycling and reuse remain crucial for achieving a circular economy and promoting green development. The built environment generates substantial urban minerals and e-waste, with a per capita scrap generation projected to reach 2.0–4.7 t cap<sup>-1</sup> by 2035 (Fig. 8). Over 90% of the scrap from the built environment consists of non-metal materials such as sand, cement, and bricks, which have a relatively small environmental impact but occupy significant space. Inadequate management may lead to land waste and soil or water pollution, affecting urban aesthetics. Over 90% of metal scraps are ferrous metals, with the remaining being copper and aluminum. Though relatively smaller in volume, metal scraps, especially e-waste, hold substantial economic value, exceeding the GDP of some countries (Forti et al., 2020). However, the current recycling capacity in China remains inadequate, handling less than 10% (Guo et al., 2019). Future policies should advocate for recycling initiatives, focusing on product design, efficiency feedback, recycling management standards, impurity removal, and the utilization of secondary materials (Fu et al., 2022). Integrating material characteristics with product functionality is key to achieving a circular economy. The transformation from raw materials to products and to services through urban “bone-muscle” metabolism hinges on material properties, forming the



**Fig. 9** “Material-stock category-sector” hierarchy and service pedigree.

basis for resource substitution and material reuse, promoting sustainable development and economic growth. In the future, China’s megacities should focus on enhancing “bone-muscle” metabolism quality. High-capacity and high-level cities should prioritize resource recycling and waste management, aiming to become comprehensive and sustainable development hubs with radiating effects, elevating public service and ecological environment to international standards. Additionally, attention should be given to adjusting the spatial distribution of the population and optimizing the population structure. By 2035, the population of megacities will basically exceed 20 million, and that of Beijing, Shanghai and Chongqing will even reach 30 million. Under the baseline scenario, the population-driven urban “bone-muscle” size will increase by 1.4–2 times to approximately 1497–6054 Mt. Moving forward, cities should adhere to policy planning objectives, mitigate potential risks posed by population growth (Zhang et al., 2015), manage the cumulative stock pressure, scale down metabolism, and sidestep the adverse effects of “big city diseases”

## METHODS

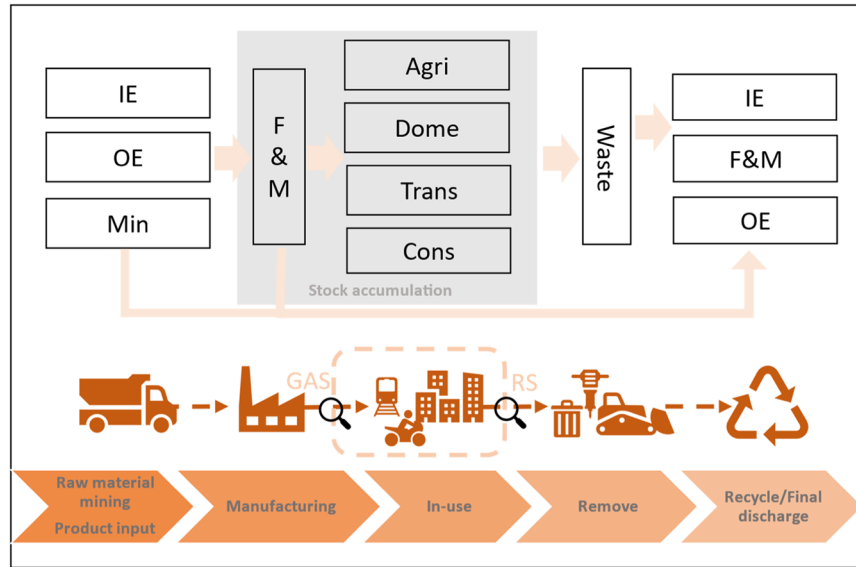
### Level-to-level pedigree of urban material stock

Urban material stocks include the built environment (including infrastructure and buildings) and durable goods (machinery and consumer durable goods, etc.), which are durable materials that have existed in the social and economic system for a long time to meet the needs of human production and life and improve human welfare. They are different from dissipative materials such as food and energy that are consumed relatively quickly and dissipated in the environment. In this study, the stock of the three categories of buildings, infrastructure, and durable goods is analyzed in detail into 12 subcategories and 111 accounting items, and an accounting framework and list of urban material stock are constructed (Supplementary Table 1, 2, 3). The stock is composed of different materials, which are mined from the environment or processed by human beings to serve all kinds of purposes. For example, sand, cement, and steel, three common substances with a broad spectrum of service categories, involve seven subcategories of stock, namely, urban residential buildings, rural residential buildings, non-residential buildings, roads, railways, pipelines, and electric lines. Changes in the subcategories will affect the use of these three substances. In this study, the evolution of in-use materials in 12 kinds of urban built environments was calculated, which were mainly divided into four categories: metal materials (steel, aluminum, and copper), nonmetallic materials (sand and gravel, cement, brick and tile, lime, glass, and ceramic), biomass materials (timber), and fossil

materials (asphalt and plastic). Buildings, infrastructure, and durable goods provide housing, work, transportation, and communication services, and the stock categories of different service functions serve different sectors. Specifically, the stock of 12 types of substances can be classified into five sectors. Industrial equipment and agricultural equipment serve the fabrication and manufacturing sector (F&M) and agriculture sector (Agri), respectively, consumer durable goods serve domestic consumption (Dome), and infrastructure such as vehicles, roads, railways, pipelines, and electric lines serve the transportation sector (Trans). Construction equipment, urban residential buildings, rural residential buildings, and nonresidential buildings serve the construction sector (Cons). The service hierarchy and service category pedigree among the materials, stocks, and sectors are shown in Fig. 9. Due to data limitations, only the built environment could be constructed, and the material service pedigree of durable goods could not be constructed at present. See Supplementary Methods for the detailed stock accounting process.

### Life cycle stock-flow network model

The static “snapshot” of material stock is formed from the accumulation of past flows and is also linked to changes in future flows. From static to dynamic, urban metabolic processes can be completely delineated. In this study, the lifespan of different stock categories is fully considered, and the input, accumulation, output and scrap processes are sorted. Life parameters and the Weibull distribution function are introduced by the dynamic material flow analysis method (see Supplementary Methods). From the perspective of metabolism, the static “snapshot” of material stock accumulation is analyzed in the dynamic transformation process of the stock-flow network, which forms a comprehensive network from the basic material unit to the product to the sector and to the city. A stock-flow dynamic metabolic network model was established for 111 types of products and 12 types of materials in 9 sectors. Figure 10 shows the cradle-to-grave life-cycle metabolism of durable materials flowing through an urban system. Using this model, it is easier to understand the input and output of various urban sectors, the direction of material and product flow, and the waste stream generated from the stock to understand how much of the city’s resources are used to realize a certain service function and how much environmental impact comes from this service function<sup>54</sup>. In this study, durable materials flow through the following 9 sectors was examined: environment (IE), other economies (OE), agriculture (Agri), mining (Min), fabrication & manufacturing (F&M), domestic consumption (Dome), construction (Constr), transportation (Trans) and waste management (Waste). See Supplementary Methods for the specific calculation process



**Fig. 10** The cradle-to-grave life-cycle metabolism of durable substances flowing through an urban system.

and Supplementary Table 4, 5, and 6 for lifetime parameters, industrial product conversion factors, and mining items.

### System robustness

System robustness ( $R$ ) is an index used to evaluate the stability and health degree of natural ecosystems and socioeconomic systems in ecological network analysis. It reflects the balance between system efficiency and diversity<sup>55</sup>. It contains two important indicators: ascendancy ( $A$ ) and redundancy ( $\Phi$ ). The sum of them is the system capacity ( $C$ ), and the proportion of dominance in system capacity is the relative order ( $a$ ). The degree of disorder of the system can be obtained by taking the logarithm function according to the degree of relative order. The product of the relative order and disorder is the robustness of the system. This index also considers the order and disorder of the system. In this study, the robustness of the system was calculated according to the node and path traffic of the dynamic metabolic network in eight cities during the historical study period. In the scenario simulation, the simulated values of new flow and scrap flow of various products in 8 cities were substituted into the network model, while the rest of the flow, such as exploitation, was substituted into the network model at the level of 2018 to calculate the robustness of the system. The specific calculation formula is as follows.  $TST$  and  $T_{..}$  represent the total flux of the system,  $T_{ij}$  represents the flow from node  $i$  to node  $j$ ,  $T_{i.}$  represents the sum of all flows from node  $i$ , and  $T_{.j}$  represents the sum of all flows to node  $j$ .

(1) Ascendancy

$$A = TST \sum \left( \frac{T_{ij}}{T_{..}} \right) \ln \left( \frac{T_{ij} T_{..}}{T_{i.} T_{.j}} \right) \quad (1)$$

(2) Redundancy

$$A = TST \sum \left( \frac{T_{ij}}{T_{..}} \right) \ln \left( \frac{T_{ij} T_{..}}{T_{i.} T_{.j}} \right) \quad (2)$$

(3) System capacity

$$C = - \sum_{ij} T_{ij} \ln \left( \frac{T_{ij}}{T_{..}} \right) \quad (3)$$

(4) Relative order

$$a = \frac{A}{C} \quad (4)$$

(5) System robustness

$$R = -a \ln(a) \quad (5)$$

### DATA AVAILABILITY

The data is available in PDF format via the Supplementary Information of this article.

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## AUTHOR CONTRIBUTIONS

Y.Z.—Conceptualization, Supervision, Funding acquisition. C.F.—Investigation, Methodology, Formal analysis, Writing. T.D.—Data curation, Visualization, Formal analysis.

## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

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