Provincial and sector-level material footprints in China

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High-income countries often outsource material demands to poorer countries along with the associated environmental damage. This phenomenon can also occur within (large) countries, such as China, which was responsible for 24 to 30% of the global material footprint (MF) between 2007 and 2010. Understanding the distribution and development of China's MF is hence critical for resource efficiency and circular economy ambitions globally. Here we present a comprehensive analysis of China's MF at the provincial and sectoral levels. We combine provincial-level input–output data with sector- and province-specific trade data, detailed material extraction data, and the global input–output database EXIOBASE. We find that some provinces have MFs equivalent to medium-sized, high-income countries and limited evidence of material decoupling. Lower-income regions with high levels of material extraction can have an MF per capita as large as developed provinces due to much higher material intensities. The higher-income south-coastal provinces have lower MF per capita than equally developed provinces. This finding relates partly to differences in economic structure but indicates the potential for improvement across provinces. Investment via capital formation is up to 4 times more resource-intensive than consumption and drives 49 to 86% of provincial-level MFs (the Organisation for Economic Co-operation and Development average is 37%). Resource-efficient production, efficient use of capital goods/infrastructure, and circular design are essential for reductions in China's MF. Policy efforts to shift to a high-quality development model may reduce material intensities, preferably while avoiding the further outsourcing of high-intensity activities to other provinces or lower-income countries.

material footprint | environmentally extended multiregional input–output (EE-MRIO) | subnational | China

Global resource extraction has risen to ∼80 to 90 billion tons per year over the last decade. This may double to 190 billion tons per year by 2060 under a historical trends scenario (1). To date, this resource use is largely linear in nature. That is, materials are extracted, refined, used, and then disposed of (2). It is widely acknowledged that a transition to a more resource-efficient, circular economy is essential to avoid tensions over access to resources and to ensure that economic development is within planetary limits (1). Given the size of its economy and related material use, China plays a crucial role. A single province can have a similar population, gross domestic product (GDP), and environmental footprint as medium-sized, high-income countries. For instance, Guangdong's GDP in 2010 was equivalent to 81% of that of the Netherlands, with a population slightly smaller than Mexico (https://databank.worldbank.org/home.aspx). China adopted the Circular Economy Promotion Law (3) in 2009, and in the 12th Five-Year Plan (2011 to 2015) set a target to increase resource productivity by 15% [defined asGDP divided by the domesticmaterial consumption (DMC) of 14 main resources (4)]. The Chinese government has also identified that development has been "unbalanced and inadequate." The government has implemented a framework to encourage high-quality development that maintains high GDP growth with low environmental impacts and resource use, as opposed to the previous high-speed growth paradigm (5).

Countries use very different amounts of material resources depending on their material endowment, population, economic structure, and income level. While higher-income countries typically have higher material footprints (MFs), these countries generally extract proportionally fewer materials from their own environments and instead import them from lower-income countries either directly or embodied in goods. This often drives environmental damage in the outsourced regions (1, 6–10). The same phenomenon can happen within countries. For instance, within China the developed coastal regions import resources and environmental damage from the less developed western and central provinces (11–15). A comparative analysis of how regions with different levels of development within countries drive resource use would provide considerable insight into how resource efficiency can be improved (7, 8).

Against this background, we examine the MF of China across provinces. The MF is a measure of the total resources required by the economy, including both consumption and capital

Significance

China has undergone unprecedented increases in material development and by 2010 drove 30% of the global material footprint (MF). Understanding China's MF distribution and development is critical for resource efficiency and circular economy ambitions globally. We combine a provincial input–output table (IOT), province-specific import–export statistics, a global IOT, and detailed extraction data to assess sector-specific and province-specific MFs in China. Capital investment—crucial to China's development—is up to 4 times more resource-intensive than consumption and comprises 49 to 86% of provincial MF. We find large differences in MF per capita across provinces, even among those with similar development characteristics. Findings indicate the need for improved understanding of material developments in other emerging countries in the 21st century.

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investments. In contrast to other indicators such as those derived from economy-wide material flow analysis (EW-MFA), the MF does not record the physical movement of materials within and among countries but describes the link between the beginning of a production chain (where raw materials are extracted from the environment) and its end (where a product or service is consumed) (16–18). Until this point, the MF has been used mainly at the country level since data limitations have precluded subnational analysis (19). To obtain a subnational database for China, we first created a material extraction database covering 29 types of resources in the 30 Chinese provinces. These become material extensions to China's intraprovincial multiregional input–output (MRIO) database with enhanced detail in resource-extracting sectors. Using a unique customs database processed for use with MRIO analysis, we embedded the Chinese provincial MRIO database in the global MRIO EXIOBASE, allowing us to trace how each sector in each province trades with other countries globally. This approach resulted in an MRIO model for 2007 and 2010 that includes 48 economic sectors, 78 regions (China's 30 provinces along with 48 world countries and regions), and 29 material extensions (for full details, see *Materials and Methods* and *SI Appendix*, sections 2.2–2.5). This model allows for analyzing how affluence, economic structure, and development influence the MF of Chinese provinces and what outsourcing patterns can be observed. Such insights are critical for resource efficiency and circular economy ambitions at the Chinese and global level and can hold important lessons for other emerging countries (20, 21).

Results

The Heterogeneous Distribution of Footprints in China. In 2010, China's MF was 23.3 Gt, ~30% of the global total (76.2 Gt). Its domestic extraction (DE) and DMC were slightly larger than its MF at 25.2 and 26.2 Gt (https://www.resourcepanel.org/global-material-flows-database), respectively. The largest MFs are found in provinces with a large GDP per capita or population: Jiangsu (1.9 Gt), Shandong (1.7 Gt), Guangdong (1.5 Gt), Zhejiang (1.4 Gt), and Sichuan (1.3 Gt; Fig. 1*A*). Jiangsu has a similar MF to that of Germany with a slightly smaller population. The coastal provinces that represent 35% of the national population generate half of national GDP and consume 40% of the total MF (9.4 Gt). However, these provinces still have a GDP per capita of only one-fifth that of the Organisation for Economic Co-operation and Development (OECD) average (https://databank.worldbank.org/home.aspx). These numbers illustrate the global relevance of China's resource efficiency and circularity ambitions, particularly since China's GDP per capita in 2010 was still only 13% of OECD members (although the gap closed to 19% by 2017) (https://databank.worldbank.org/home.aspx). Additionally, the coastal provinces generally have a smaller DE than MF, whereas the reverse is true for the inland provinces (*SI Appendix*, Table S1). This finding is consistent with the different roles of provinces within the economy (i.e., resource suppliers vs. resource consumers).

On average, China's MF was 17.5 tons per capita in 2010, of which 12% was biomass, 17% fossil fuels, 8% metals, and 62% nonmetallic minerals. This places China between the global average of 11 tons per capita and developed OECD countries of 24 tons (https://databank.worldbank.org/home.aspx and https://www.resourcepanel.org/global-material-flows-database). The contribution of nonmetallic minerals in China (62%) is high compared to the global average (45%). Comparative studies at the country level show that affluent countries have an MF per capita up to 10 times higher than low-income countries (1, 7). This phenomenon, although in a more moderate form, is also observed within China (Fig. 1 *B* and *C*). Affluent megacities with a GDP per capita of around 40,000 Yuan (~6,000 USD) or more such as Shanghai and Beijing and coastal provinces such as Zhejiang and Jiangsu have MFs per capita of between 25 and 33 tons. In contrast, Guizhou, a southwest province with a GDP per capita of just 13,000 Yuan (~1,900 USD), has an MF per capita of just 10 tons.

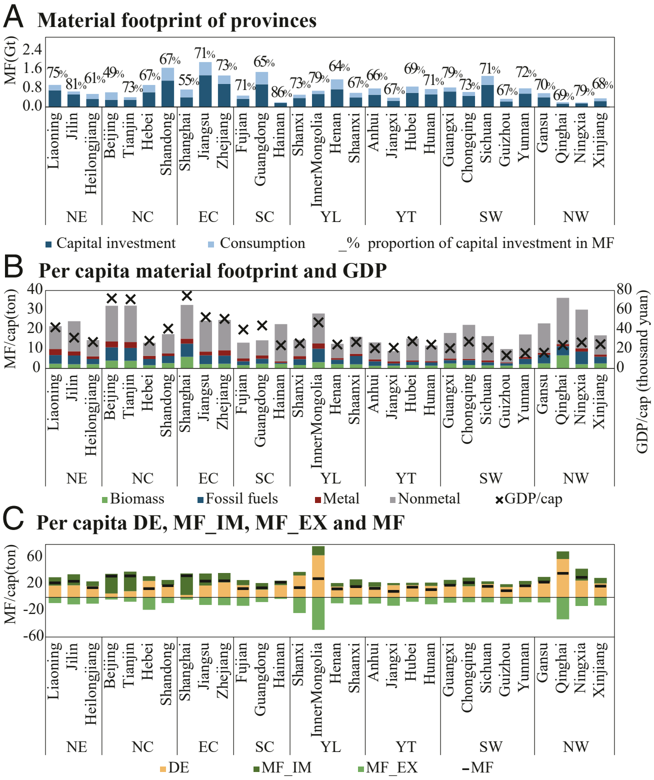
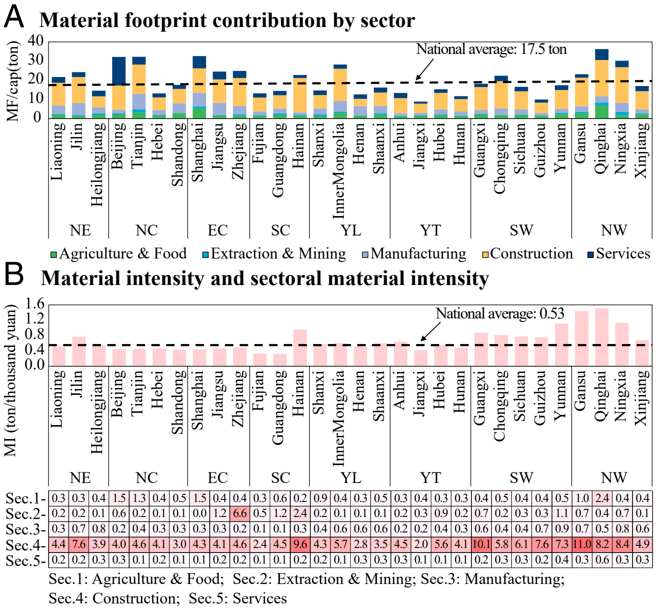


Fig. 1. (*A*) The contributions from capital investment (dark blue) and consumption (light blue) to the overall MF in each province/city. The percentages show the proportion of the MF flowing to capital investment. (*B*) Per capita MF of biomass (shown in green), fossil fuels (blue), metal (red) and nonmetallic minerals (gray), and GDP (crosses). (*C*) Per capita DE, material imports embodied in trade (MF_IM), material exports embodied in trade (MF_EX), and MF (black bars). All data are for 2010. The capitalized abbreviations give the region to which a province belongs: NE, northeast; NC, north coast; YL, Yellow River midstream; YT, Yangtze River midstream; EC, east coast; SC, south coast; SW, southwest; NW, northwest.

The largest per capita MFs are found in less developed provinces. The MF of Qinghai at 36 tons per capita is similar to the United States but with a GDP per capita of only 24,000 Yuan (~3,500 USD, 7% of the United States). Other provinces located in the less developed northern and western regions, Ningxia, Inner Mongolia, and Gansu, show similarly high MFs per capita of 30, 28, and 23 tons, respectively. The share of nonmetallic minerals in MFs across western provinces (55 to 78%) is much higher than in high-income provinces (~50%) (Fig. 1*B*). Western provinces are in a relatively early stage of urbanization and industrialization but are developing quickly and catching up with coastal regions. Consequently, the large material demands across western provinces are created primarily by the construction sector (Fig. 2*A*). Additionally, the biomass footprint of Qinghai reached 7 tons, higher than that of the most developed regions (e.g., 6 tons in Shanghai), due to the high level of animal husbandry and the direct use of biomass for energy (22).

Interestingly, per capita MFs in the developed south coast provinces such as Guangdong and Fujian are among the lowest at around 14 tons. This is much lower than across east coast provinces with comparable development levels and similar GDP, such as Jiangsu and Zhejiang. At first sight, this result suggests a potential to improve the MF in east coast provinces. However, looking more closely, the differences may be caused



	Liaoning	Jilin	Heilongjiang	Beijing	Tianjin	Hebei	Shandong	Shanghai	Jiangsu	Zhejiang	Fujian	Guangdong	Hainan	Shanxi	InnerMongolia
Sec.1-	0.3	0.3	0.4	1.5	1.3	0.4	0.5	1.5	0.4	0.4	0.3	0.6	0.2	0.9	0.4
Sec.2-	0.2	0.2	0.1	0.6	0.2	0.1	0.1	0.0	1.2	6.6	0.5	1.2	2.4	0.2	0.1
Sec.3-	0.3	0.7	0.8	0.2	0.4	0.3	0.3	0.3	0.3	0.2	0.1	0.1	0.3	0.4	0.6
Sec.4-	4.4	7.6	3.9	4.0	4.6	4.1	3.0	4.3	4.1	4.6	2.4	4.5	9.6	4.3	5.7
Sec.5-	0.2	0.2	0.3	0.3	0.1	0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.2	0.1

	Henan	Shaanxi	Anhui	Jiangxi	Hubei	Hunan	Guangxi	Chongqing	Sichuan	Guizhou	Yunnan	Gansu	Qinghai	Ningxia	Xinjiang
Sec.1-	0.3	0.5	0.3	0.4	0.3	0.3	0.4	0.5	0.4	0.4	0.5	1.0	2.4	0.4	0.4
Sec.2-	0.1	0.1	0.2	0.3	0.9	0.2	0.7	0.2	0.3	0.3	1.1	0.7	0.4	0.7	0.1
Sec.3-	0.6	0.6	0.2	0.2	0.4	0.3	0.6	0.4	0.4	0.7	0.9	0.7	0.5	0.8	0.6
Sec.4-	2.8	3.5	4.5	2.0	5.6	4.1	10.1	5.8	6.1	7.6	7.3	11.0	8.2	8.4	4.9
Sec.5-	0.3	0.3	0.3	0.1	0.1	0.1	0.2	0.3	0.3	0.2	0.4	0.3	0.6	0.3	0.3

Fig. 2. (*A*) Sectoral contributions to the MF in each province/city. (*B*) Material intensity (MI) and sectoral material intensities. Each cell in the mesh grid shows the material intensity per sector and province, with the scale indicated in red. All data are for 2010. The capitalized abbreviations give the region to which a province belongs: NE, northeast; NC, north coast; YL, Yellow River midstream; YT, Yangtze River midstream; EC, east coast; SC, south coast; SW, southwest; NW, northwest.

predominately by variations in the economic structure. South coast provinces such as Guangdong have lower capital investment per capita, especially in real estate and manufacturing (*SI Appendix*, Fig. S2*A*). Since capital investment has a high material intensity, this difference leads to a relatively low MF of investment in south coast provinces (*SI Appendix*, Fig. S3*A*). Guangdong has a relatively high output of final consumer goods, which typically generate a high percentage of value added (*SI Appendix*, Fig. S4). The east coast has a relatively high output of intermediate industrial products from capital-intensive industries, such as chemicals, which typically generate a low percentage of value added (*SI Appendix*, Fig. S5). The focus on final consumer goods across the south coast seems to explain how it achieves a lower MF for a similar GDP per capita as more materially intensive provinces.

As a rapidly developing country, China has a capital investment-driven economy. Capital investment in China is 51% of GDP, with variations across the provinces between 44 and 66%. Capital investment is up to 4 times more resource-intensive than consumption (on average it is twice as intensive; *SI Appendix*, Table S6). As a consequence, 61 to 86% of provincial MFs are driven by capital investment, with the exception of megacities Beijing (49%) and Shanghai (55%; Fig. 1*A*). In contrast, capital investment in OECD countries is on average 21% of GDP (https://databank.worldbank.org/home.aspx) and responsible for just 37% of the MF (23). The MF of capital investment is primarily driven by construction (47 to 92% of the total), with machinery and equipment a distant second (*SI Appendix*, Fig. S3). Given the size of the construction sector, it dominates the MF both nationally (at 52%) and regionally (30 to 79%) with almost 10 times the material intensity of the average of all sectors nationally (Fig. 2*B*). Although the input–output models we applied are not detailed enough to analyze the material intensities of different types of capital investment in high resolution (e.g., separating out infrastructure and real estate), we used provincial-level statistics to gain some insight (*SI Appendix*, Fig. S2). Real estate, infrastructure, and manufacturing dominate investment expenditures (24). For most provinces, infrastructure accounts for a large share of investment (21 to 55%), especially in the western provinces such as Gansu (55%), Yunnan (51%), Guizhou (44%), and Inner Mongolia (43%). In Beijing and Shanghai, as well as Hainan, most investments (40 to 59%) are in real estate. Investment in manufacturing is dominant in provinces such as Jiangxi (51%), Jiangsu (50%), Jilin (44%), and Shandong (41%). Services in Beijing drive ∼50% of the MF. This result is consistent with the fact that the country's capital has a predominately service-oriented economy. Further, no less than 45 to 75% of the fossil fuel footprint is related to capital investment, indicating the crucial role of resource use for Chinese infrastructure in climate policy (*SI Appendix*, Fig. S8).

There are large differences in material intensity (MF per unit of GDP) among sectors and provinces. Much higher material intensities are found in almost all sectors across western regions (Fig. 2*B*). The provinces in the west, Qinghai, Ningxia, and Gansu, have material intensities that are twice the national average. This difference could be caused by the time lag between investments in material-intensive new infrastructure and the economic benefits from using this infrastructure (25). The developed coastal areas are below the national average in material intensities (except Hainan which experienced a construction boom). This finding may in part reflect price variations: the value of real estate in Shanghai dwarfs the value of real estate in the west. However, it is clear that the west has a disproportionate MF compared to GDP.

Outsourcing MF. The material transfers embodied in interprovincial Chinese trade are extremely large. In 2010, ∼12.4 Gt (53%) of the total Chinese material consumption was embodied in interprovincial and international trade. Within these material transfers, 9.6 Gt originates from DE, and 2.8 Gt is extracted abroad (*SI Appendix*, Table S7). The embodied interprovincial material transfer within China is almost equal to the total MF of the United States (at 9.8 Gt [https://www.resourcepanel.org/global-material-flows-database]). On a provincial level, we find similar MF patterns as those between countries at the global scale (7–10) and provincial-level footprint studies for carbon, PM2.5, and SO_2 (11–15): material demands in affluent areas are supported by extraction and production in less-developed areas. There are 12 provinces, located mainly along the coasts, which are net national and international MF importers (Fig. 1*C*) with material inflows (per capita) up to 3.5 times the national average. The remaining 18 provinces, mainly located in the north and west, are net exporters, particularly Qinghai, Inner Mongolia, Shanxi, and Hebei, with outflows (per capita) of between 1.7 and 4.5 times the national average. These provinces sit in regions which are major suppliers of materials: biomass from the northeast and southeast, fossil fuels from the Yellow River midstream area (Shanxi and Inner Mongolia), and metals from the north coast (Hebei). The domestic virtual transfers of nonmetallic minerals are geographically closer than those of other types of resources due to the properties of these minerals: low value, easy to obtain, versatile, and high transport costs compared to value per unit of mass (26) (see Fig. 3 with provinces grouped into clusters and *SI Appendix*, Tables S8 and S11 and Figs. S17–S22, for detailed information on provinces). Not surprisingly, the city-provinces of Shanghai, Beijing, and Tianjin have almost no DE, relying almost entirely (92 to 99%) on imports (both interprovincial and international; *SI Appendix*, Fig. S17). In comparison, the MF of inland areas is mostly satisfied by local or DE (56 to 76%), which decreases to 31 to 38% in the east and south coasts (Fig. 3). Material outsourcing patterns also show large material leakages as the virtual flow almost always runs from regions with a high material intensity to areas with a low intensity (compare Figs. 2*B* and 3) (12, 13).

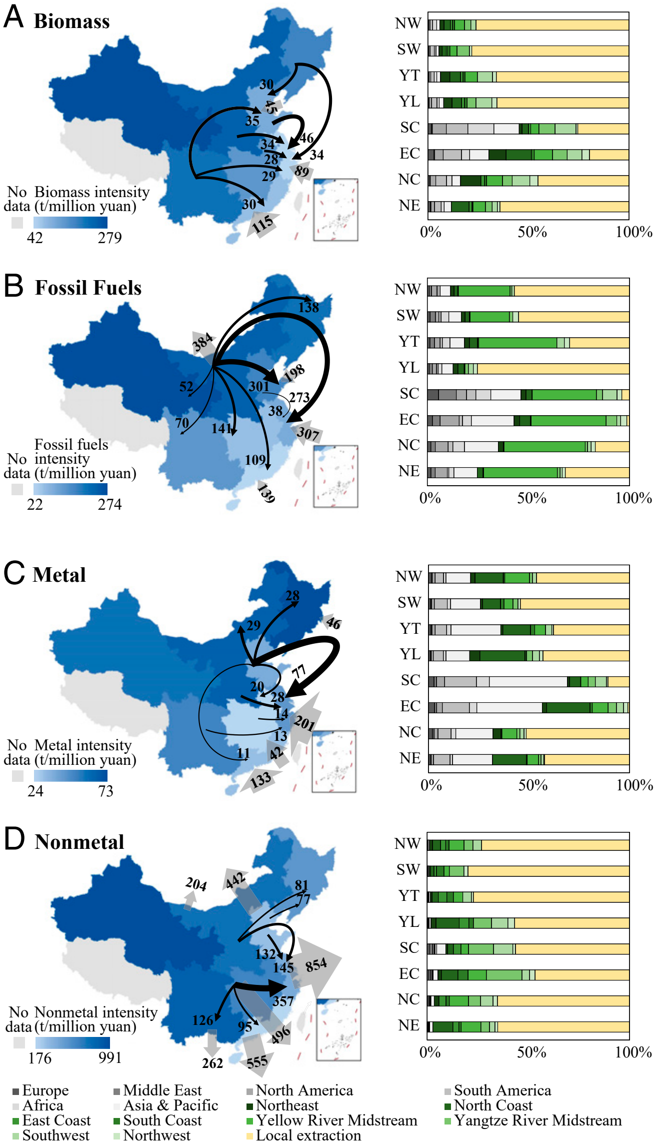


Fig. 3. Net resource transfer embodied in trade in 2010: (*A*) biomass, (*B*) fossil fuels, (*C*) metal, and (*D*) nonmetal. The top 8 fluxes and international fluxes are included (in million ton). The domestic transfers (black arrows) and international transfers (gray arrows) are shown. The arrows in each figure have different scales for ease of inspection. See *SI Appendix*, Table S8, for detailed amounts of the fluxes. Colors indicate the material intensity of each resource. Bar charts show the outsourced origin of the MF for different regions in percentages for each cluster of provinces. See *SI Appendix*, Figs. S17–S22, for the provincial level information. The capitalized abbreviations give the region to which the province belongs: NE, northeast; NC, north coast; YL, Yellow River midstream; YT, Yangtze River midstream; EC, east coast; SC, south coast; SW, southwest; NW, northwest.

Fig. 3 shows the net transfers embodied in trade by raw material type and region. China relies on raw materials embodied in imports for 17% of the biomass footprint, 28% of the fossil energy footprint, and 39% of the metal footprint. China is a net exporter only of nonmetallic minerals. The coastal areas rely more on material extraction abroad than the inland areas. The MFs of the south and east coasts have the highest reliance on embodied resources in imports (30 to 45% of biomass, 43 to 46% of fossil energy, and 57 to 69% of metals). Overall, these imports account for half of the MF imports into China (1.4 Gt). The less-developed inland provinces have a much lower proportion of the MF satisfied with imports (just 6 to 8% of the biomass, 12 to 18% of fossil resources, and 21 to 36% of metals). Nearly half of China's MF embodied in imports is sourced from the Asia Pacific region. Although China is a net importer of fossil fuels, there is a large net flow (384 Mt) of fossil energy embodied in products for international exports from the Yellow River midstream region (where major coal mines are located).

Trends in MFs. Fig. 4 compares the provincial level footprints between 2007 and 2010. While an analysis over a longer time period would have been desirable, it is currently not possible given the availability of all required datasets for other years. Between 2007 and 2010, China's MF grew faster (11.6% y^{-1}) than its GDP (9.9% y^{-1}). There was limited evidence of a relative material decoupling, with only one-third of provinces showing slower MF growth than GDP growth. The highest levels of relative decoupling were seen in Shanghai, Zhejiang, Chongqing, and Jiangxi where the annual MF growth rates were ~9% and lower than the 9 to 15% y^{-1} GDP growth rates. For some western provinces (e.g., Inner Mongolia, Gansu, and Qinghai) and Hainan Island, the opposite occurred: the MF growth rate was up to 2 times the GDP growth rate during this period.

We find some evidence that policies such as the China Western Development Program (27) may have helped lift the economic growth of underdeveloped provinces. These provinces saw a 13% increase in GDP between 2007 and 2010, which was faster than in coastal areas (11%). However, these provinces did so with a 14% growth in MF on average over the same period. Investment in construction and rapid urbanization are likely contributing factors in regions that previously had low urbanization levels of 40% or less (*SI Appendix*, Figs. S3, S23, and S24). Although it is possible to perform a decomposition analysis for the 3 y (2007 to 2010), data limitations preclude analysis over a longer period (over which long-term trends could be identified). The decomposition for 2007 to 2010 (elaborated in *SI Appendix*, section 1.2) suggests that most provinces have become more, not less, material-intensive, particularly across western provinces. These provinces have significantly increased their material intensities (contributing between 14 and 40% of their MF growth). Additionally, migration effects are large enough to be clearly seen in the changing MF across China.

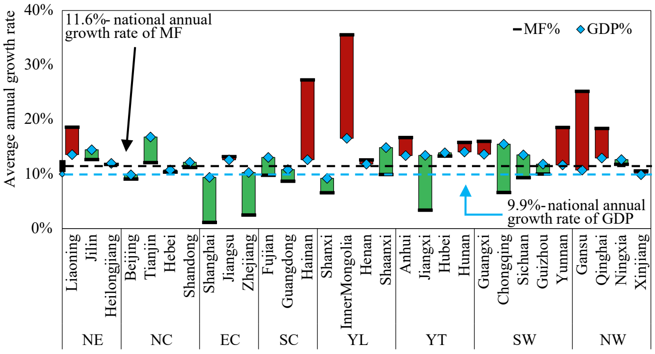


Fig. 4. Average annual MF (black bars) and GDP (blue diamonds) growth rates for 30 provinces/cities in China between 2007 and 2010. The columns show the gaps between the 2 rates of change with green indicating GDP growth exceeds MF growth (relative decoupling) and red the reverse. The national average is shown on the left. The capitalized abbreviations give the region to which a province belongs: NE, northeast; NC, north coast; YL, Yellow River midstream; YT, Yangtze River midstream; EC, east coast; SC, south coast; SW, southwest; NW, northwest.

Discussion

China's MF in 2010 comprised ~30% of the global total, and its per capita MF reached 17.5 tons, a level 1.6 times higher than the global per capita average but lower than the per capita average in OECD countries (~70%). In contrast, China's GDP per capita was 48% of the world average and just 13% of that of OECD member states. An indicative comparison of the MFs between 2007 and 2010 gave no evidence of decoupling. Two-thirds of the provinces were becoming more, not less, material-intensive over this period. This illustrates the relevance of China's ambition to improve resource efficiency and to embark upon high-quality development as opposed to the previous aim of high-speed growth (5). The MF per capita differs by a factor of 4 between provinces. This difference may seem large on a national scale but is generally less pronounced than between countries at the global scale. Similar to patterns found across countries, less developed provinces export low value-added and material-intensive primary resources or intermediate goods (1, 7).

Capital investment is an important explanatory variable for differences in provincial MFs. Capital investment is up to 4 times as resource-intensive as other final consumption and comprises 43 to 66% of provincial GDP. This high level of capital investment is typical for a fast-developing economy (1) and contrasts with the OECD average of 21%. As a result, 49 to 86% of the provincial MFs are caused by capital investment. The root cause of the high level of investment-driven material use is China's rapidly expanding construction sector, but the forms of this construction vary across the country. Real estate dominates in high-income provinces, while infrastructure dominates in lower-income provinces. Almost all material input due to capital investment will accumulate as in-use stocks (28). The large gaps in investment-driven MF between China's provinces and OECD members are to some extent due to the gaps between accumulated infrastructure and capital goods. It can be assumed that the investment-driven mode of material accumulation across most Chinese provinces would continue since sufficient capital goods and in-use stocks are generally prerequisites for productivity and economic growth (28). Capital investment also drives a further 62% of the Chinese fossil fuel footprint, which is important because the production of materials for infrastructure construction such as cement, steel, and copper is generally harder to decarbonize than other sectors (29).

Usually, MFs are closely correlated with GDP (1, 8). However, we find that provinces at similar development levels can have significantly different MFs. For instance, the MF in the lower-income western province of Qinghai is 36 tons per capita, similar to that in the United States (https://www.resourcepanel.org/global-material-flows-database), which contrasts distinctly with the 10 to 20 tons per capita in many provinces in central China. It also contrasts with global trends where low-income regions tend to have low per capita MFs (1). This difference can in part be explained by the investment in infrastructure and urbanization across western provinces as supported by large-scale national policies (i.e., the China Western Development Strategy (27)). Over half of these high MFs in China's provinces are from sand and gravel which are both high-volume/low-value resources that are mostly for in-use stocks in infrastructure and construction. The per capita MFs of the lower-income western provinces are already equivalent to the most affluent areas in China. A significant question is whether these MFs might be reduced in the future. Additional information on the current, accumulated stocks would be needed to give a definitive answer. Given different natural and economic contexts, these provinces are likely to have different development paths compared to megacities such as Beijing and Shanghai. As a large part of the MFs in most provinces are currently driven by investment, it is important that these capital goods are produced as efficiently as possible and are designed with circularity principles in mind (e.g., for future reuse and refurbishing) (30, 31). Among high-income regions, the east coast has an MF of 25 tons per capita or more, while for the south coast this is around 14 tons. Here we find that the south coast has a larger focus on less capital-intensive, high value-added final consumer industries.

In sum, the observed differences in MFs across China's provinces are explained by a combination of natural (i.e., resource endowment) and economic contexts (i.e., economic structure and the extent to which a province is integrated with trade) (29). For instance, although coastal provinces are resource-poor compared to other regions, they have taken advantage of policies (i.e., economic reform and opening of markets), location (marine access), and trade (especially for international trade). Consequently, these provinces have seen greater economic growth, as shown by their large MFs. Material extraction is highly concentrated in the central and western regions, with 15 out of 30 provinces responsible for over 80% of DE of both fossil fuels and metal minerals. China's ambition to shift to a high-quality development paradigm that relies less on low value-added and heavy industries would help realize a lower MF for both affluent and less-developed provinces. However, a concern is that affluent provinces might further outsource their own low value-added and resource-intensive industries to less developed provinces or to lower-income countries via trade in products and services. Furthermore, once sufficient capital goods and infrastructure have been accumulated, similar to the accumulation already seen in most OECD countries, GDP may be driven more by consumption as opposed to investment. This shift might lead to decoupling since consumption expenditure is generally less material-intensive than investments. However, true decoupling should rely on implementing resource-efficient approaches and technologies along with circular designs (1).

Future studies will need to increase the sectoral resolution for the sectors contributing most to China's MF, in particular, infrastructure and real estate (20). Bottom-up analyses of physical material requirements per unit of output by sector and across provinces will avoid potential biases caused by price differences between provinces that may be present in top-down studies (32). Expanded time series data will also be a priority. We also recommend complementing the DMC indicator (which largely reflects DE), now the basis for China's policy targets, with the MF (which reflects global material extraction for satisfying consumption in a country) (1). In the long term, we recommend incorporating in-use stocks into assessments (these stocks are mostly investment-driven and accumulated materials). The collection of these data could help identify whether there are still large gaps between in-use stocks in China and its provinces when compared to other developed countries with similar economic structures.

Capital investment is a critical area of attention for China's resource efficiency and (future) circularity potential. This aspect is equally true for other investment-driven economies that are in a fast development phase. An expanding capital stock inevitably needs primary materials, and capital stocks can reside for decades in the economic system before becoming available for reuse (28). It is essential to produce such capital stocks as resource-efficiently as possible and, more importantly, to already design such capital stocks for circularity (33).

Materials and Methods

Construction of China's Provincial DE Database. When constructing China's provincial-level DE database, we based it on the classification used by Eurostat in its EW-MFA (34). We discerned the usual 4 main categories (biomass, fossil fuels, metal, and nonmetallic resources), 13 subcategories, and 29 specific types of resources. China does not have consolidated data for all types of resource extractions by province at the national level. We therefore used in part provincial statistics or estimated the resource extraction by province using methods and coefficients recommended by government research programs, national pilot surveys on the circular economy in China (35, 36), and Eurostat (34) (*SI Appendix*, section 2.2). The DE values in other countries and regions were obtained from EXIOBASE environmental satellite accounts, which in turn are based on the global material flow database of the United Nations International Resources Panel (37, 38). The total DE for China in our provincial database deviates just by 1% from the DE for China in these sources.

Linking the Chinese MRIO to GMRIO. To enable provincial-level footprint calculations in a global context, we linked the Chinese MRIO (CN-MRIO) database (39, 40) to the global MRIO database EXIOBASE (37, 41–43). Such an integration of the Chinese MRIO with a global MRIO has been performed by various research groups before (12, 44, 45), but none of the previous efforts created additional sector details with a focus on resources. We used as a basis the official CN-MRIO database compiled by the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences and the National Bureau of Statistics (39, 40). This MRIO covers 30 provincial regions (26 provinces and 4 cities) and 30 economic sectors for each province. We used EXIOBASE v3.4 (41) for 2007 and 2010, which discerns 49 countries and regions including China, 163 economic sectors by country, and detailed environmental extensions (https://www.exiobase.eu/). The integration was performed as follows. First, the total volume of the Chinese MRIO was rescaled to match the sum of China's matrix in EXIOBASE including harmonizing currencies based on market exchange rates. We then created a harmonized sector classification by disaggregating particularly the resource extracting sectors in the Chinese MRIO and aggregating sectors in EXIOBASE to 48 sectors (*SI Appendix*, sections 2.2 and 2.4). The input–output relations of disaggregated sectors in a province were assumed to be distributed in the same proportion as China's national level for those sectors. To fully reflect the regional differences, provincial-level customs data of China were adopted to disaggregate Chinese imports and exports into each sector in each province. This process was based on shares of sector-specific and province-specific import and export data, which include international trade information for all provinces with product specifics. Finally, a biproportional adjustment was employed to balance the input–output table. The linked CN-GMRIO includes 78 regions (the original 48 counties and regions in EXIOBASE excluding China and 30 Chinese provinces/cities) with 48 economic sectors.

Calculating MFs. Using the EE-MRIO database depicted above, we apply the Leontief model (46, 47) to calculate the MF per sector and province, an approach that is now standard in environmental footprint analysis (9, 48). The MF can be calculated as follows:

$$MF = \sum_{r} k_i^r \sum_{j,t} l_{i,j}^r y_j^r,$$

where *MF* is a vector constituted by *MF* in every economic sector for each region; k_i^r is the intensity matrix indicating DE per unit of each economic sector's total output in each sector i in each region r; $l_{i,j}^r$ is the Leontief inverse matrix, representing the total economy-wide requirements from row sector j to produce a unit of output from column sector i; and y_j^r is the final demand matrix.

Data availability is indicated in *SI Appendix*, section 2.6.

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