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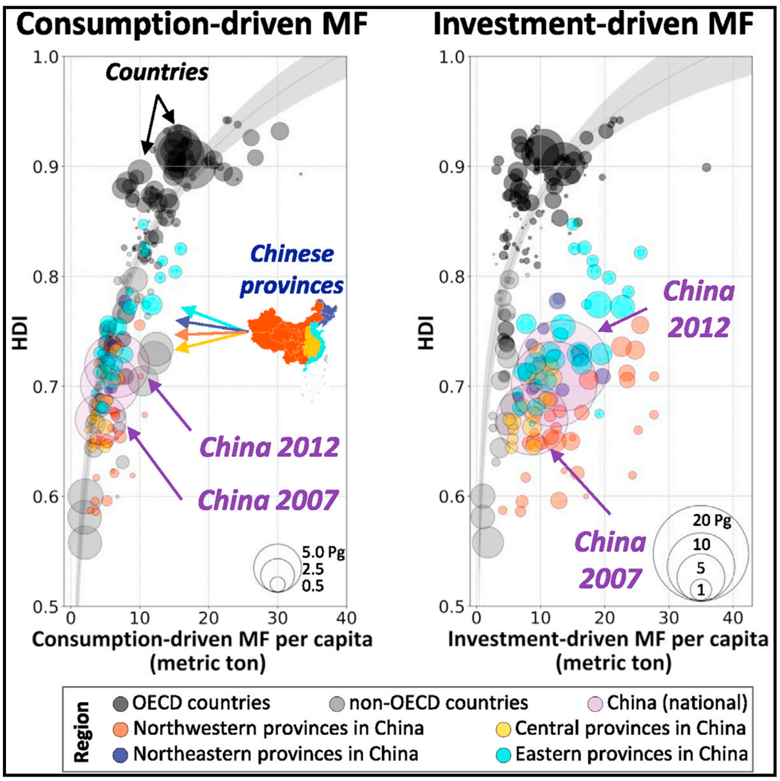
Different Material Footprint Trends between China and the World in 2007-2012 Explained by Construction- and Manufacturing-associated Investment

Graphical abstract



Highlights

- China's growing material footprint (MF) shows a different development trajectory
- Poorer provinces had larger MF/cap than nations with similar Human Development Index
- China's different MF trajectory can be mainly explained by high capital investments
- The investment-associated-driven proportion of MFs in China can be as high as 82%

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In brief

Historically, human development has been deeply rooted in the extraction and processing of resources, with socio-environmental consequences. China's material footprint (MF) has grown rapidly in recent decades, but the underlying mechanisms remain unclear. Using global input-output models, we find that investments associated with construction and manufacturing triggered the majority of China's MFs, indicating that capital investment activities enabling growth can lead to more intensive material exploitation. We recommend incorporating broader sustainability into investment plans to facilitate sustainable development pathways.

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Different Material Footprint Trends between China and the World in 2007-2012 Explained by Construction- and Manufacturing-associated Investment

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SCIENCE FOR SOCIETY As countries grow more prosperous, quality of life improves. However, development relies on the mining and processing of materials, which have a number of negative impacts on society and the environment, compromising sustainable development goals. Decoupling material use from human development is essential if we are to realize a truly sustainable future, but our understanding of the complex relationships that connect these two issues is poor. Using China as an example, we assessed the flows of biomass, fossil fuels, metals, and non-metal minerals in and beyond China's provinces between 2007 and 2012. We find that development in China, especially in poorer provinces, was intensively associated with material use and generated much larger material footprints than other nations. The majority of these footprints were driven by capital investments in construction and manufacturing. Our findings indicate an urgent need to consider the wider sustainability ramifications of capital investment.

SUMMARY

Economic prosperity is vital to human development but relies heavily on material extraction, which causes environmental degradation. To successfully decouple growth from degradation, it is essential to identify the primary drivers of countries' material footprints (MFs). However, such understanding remains limited due to the complexities of investment- versus consumption-driven growth. Here, we focus on the MF of China between 2007 and 2012, which was responsible for 24%–30% of global material use. We adopt input-output models that consider trade and classify investment/consumption to estimate, at the province level, the relationship between MFs and the Human Development Index (HDI). Results show that during 2007–2012, China's per capita MF mirrored its HDI and increased by nearly 20%. This is especially prominent in poorer provinces. We further find that it was investments, particularly capital investments associated with construction and manufacturing, that dominated China's MF rather than a consumption-driven demand. Given vast infrastructure gaps in emerging economies and post-pandemic investment plans, these findings emphasize the need for a better understanding of the drivers of growth.

INTRODUCTION

Since the 1970s, the global population has almost doubled while material extraction has tripled.[1] The global average material demand per capita was 7.4 t (metric tons) in 1970 and grew to 12.2 t by 2017.[2] The extraction and processing of materials drive around half of the total global greenhouse gas (GHG) emissions, accounting for large amounts of biodiversity loss, and drive water stress.[2] These issues are set to become increasingly acute given the expected doubling of global material demand to 190 billion (metric) tons or 18.5 t per capita by 2060, as estimated by the UN Environment International Resources Panel (UNEP-IRP) in its "historical trends" scenario.[2]

While researchers and commentators have assumed that economic growth would ultimately lead to a decoupling between consumption and material use, a previous consumption-based investigation showed that in all developed economies, the material footprint has kept pace with the economic growth, and the improvements in resource efficiency are few, indicating no evidence of decoupling in the group of developed economies in the last two decades.[3,4] In certain developing countries, decoupling has been observed, but these emerging markets are expected to most contribute to future material growth and may follow the coupling trends of developed economies as outlined above.[5] In addition, another investigation on material stocks proved that global additions to material stocks in all materials used between 1900 and 2010 rose from 18% to 55%. This suggests that in-use capital stocks and gross domestic product (GDP) are correlated and deeply coupled.[6]

Given these challenges, several scientific and policy communities have underlined the urgent need to factor material use and environmental footprints into economic growth and human development indexes.[1,2,7] A prime example includes the recent updates to the Human Development Index (HDI). Adopted by the United Nations Development Program (UNDP), the HDI is perhaps the most high-profile summary composite index of development. Previously, the HDI identified a nation's human development level based on three key aspects: health (life expectancy), knowledge (education), and standard of living (income).[7,8] In 2020, the 30th anniversary edition of the Human Development Report[7] added two further components to the index, national (per capita) material footprint and carbon dioxide emissions,[7] emphasizing the importance of considering these two factors in evaluating the wellbeing of human development. HDI scores range from 0 to 1. An HDI above 0.7 is seen as a level of high human development and below 0.6 is low generally.

Despite the welcome inclusion of material-related environmental externalities into the HDI, our understanding of the complex relationship between resource exploitation and economic development remains limited, and evidence of the decoupling of development and material use is often conflicting. Two approaches are commonly used to measure the material use of an economy: the first approach is domestic material consumption (DMC), which equals the domestic extraction of raw materials plus the weight of imported goods minus the weight of exported goods. Material productivity is then given by the GDP divided by the DMC. Based on this approach, the decoupling of GDP from DMC growth has been observed in some nations.[1] However, the DMC omits primary resources extracted to produce traded products.[3] To address this, the second approach used raw material consumption (RMC) instead of DMC. The RMC measures the material footprint (MF), that is, the primary resource extraction, domestically and abroad, required to produce the final demand for goods and services of a specific country in a specific year.[3] This framework allocates all raw materials extracted across the world and used directly or indirectly in the domestic final demand of nations.[9] This approach also embeds a life-cycle perspective since the trade and global supply chain are considered. Previous studies have shown that when taking trade into account via the RMC approach, there is little evidence of decoupling.[1–3]

While the RMC approach uncovered that, at large, the MF and economic development remain coupled, the drivers behind the coupling relationship remain under-explored, preventing effective decoupling. Normally, the development of an economy is determined by domestic and non-domestic investments (e.g., investments such as gross fixed capital formation mainly associated with buildings, infrastructures, and equipment) and consumption (e.g., household and government expenditure), but measures to help effectively decouple economic development from material exploitation will depend on clearly understanding the primary driver.

China's economy and material use have grown rapidly over the few past decades, as reflected by the HDI. During 2007–2012, China drove 24%–30% of the current global resource extraction,[2,10] making it an excellent example for exploring how material use is coupled with development. Furthermore, given the large differences in development levels between Chinese provinces,[11,12] dynamics within China can, to an extent, be considered a microcosm of global dynamics. For example, a recent study on China's subnational HDI found a variation of 0.56–0.85 across provinces from 2007 to 2012, which was analogous to a variation between Bangladesh and Spain.[11–13] Our previous work has also shown that less developed western provinces in China can have MFs per capita larger than developed OECD countries;[10,11] it is, therefore, important to investigate such economic development and material use dynamics at the provincial level.

Here, we use global input-output models that consider trade to estimate the relationship between the MF and HDI in China at the province level between 2007 and 2012, as well as the MF relative to global countries. Four categories of materials are included in the analysis: biomass, fossil fuels, metals, and non-metallic minerals. We classify the use of these materials into investment- and consumption-driven categories. The investment-driven MF refers to the gross fixed capital formation (GFCF) and inventory, and the consumption-driven MF refers to household and government expenditures. These two MFs sum to the total MF of a region (i.e., there is no residual MF). Please see experimental procedures for more details. We find that, before 2007, only 7 of 31 provinces in mainland China had an HDI above 0.7, but as soon as 2012, 26 provinces attained a similarly high HDI level. This rapid HDI progress was, however, accompanied by significant material use: the per capita MF of China increased from 13.0 t (7.0–33.6 t across provinces) in 2007 to 20.2 t (13.2–38.4 t across provinces) in 2012. Some lower-income provinces in western China have higher MF per capita than affluent provinces. Interestingly, capital investment was the key driver of MFs,

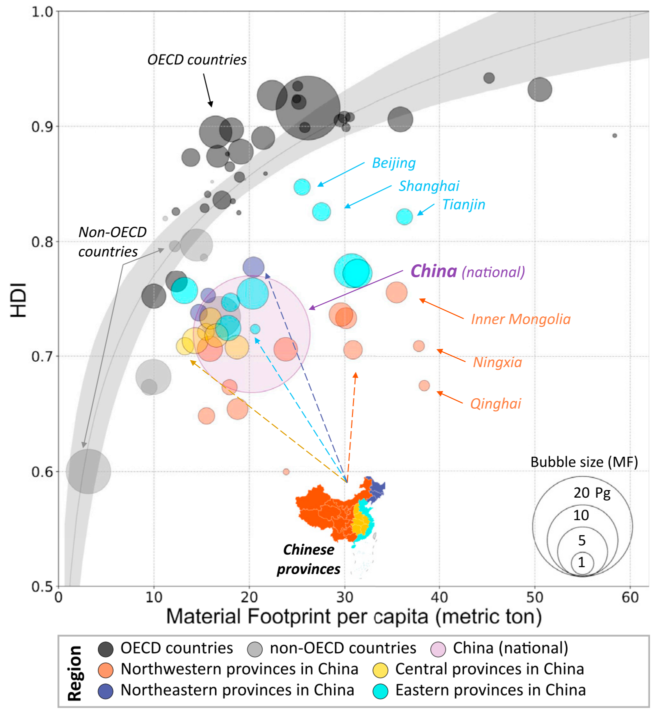

Figure 1. The relationship between the human development index (HDI) and the per-capita material footprint

Bubble size represents the overall material footprint driven by an economy (country/region/province). The trendline represents the logarithmic relationship between the HDI and the per-capita material footprint among countries. The 95% confidence interval is indicated by the shaded area. Results are for 2012. Bubble size is given as Pg (petagram, equivalent to one billion metric tons) of material. See Figures S1 and S2 for pooled results of 2007, 2010, and 2012 along with the relationship between three different HDI dimensions and the per-capita material footprint (MF). Both bubble charts and marker charts showing the same information are shown in Figures S2 and S6.

particularly the use of non-metallic minerals for construction (buildings and infrastructures) and manufacturing (equipment and machinery) development. This phenomenon is especially prominent in poorer provinces, where MFs per capita were up to twice that of other countries with the same HDI. These results indicate that the rapid development in China, especially in less developed provinces, was enabled by intensive investments associated with buildings, infrastructures, and manufacturing, leading to substantial material use. Our findings indicate an urgent need to consider the wider sustainability implications of future investment plans.

RESULTS

China's complex MF

Previous works have shown that higher living standards (measured as GDP or HDI) are generally related to higher per-capita MFs.[1,2,5,11,14,15] We also find a strong correlation between MFs and wellbeing indicators for most countries (see Figures 1, S1, and S2 for HDI; Figure S3 for subdimensions of HDI; and Figures S4, S5, S7, and S8 for GDP). For example, in 2017, the MF of high-income countries was ~27 t per capita, 60% higher than middle-income countries and 1,300% higher than low-income economies. In Figure 1, we show the HDI and per-capita MF for China as a whole (purple bubble) and individual Chinese provinces (yellow, orange, light blue, and dark blue bubbles). We see that country-level data fit well in the logarithmic relationship previously established by other work,[1,7,14–22] but that there is no good fit for many of China's provinces (see further statistical details in Table S2).

Western provinces show a large deviation from the general trend. Many of China's less developed western provinces have a relatively low HDI (0.6–0.7) but an MF of over 30 t per capita (e.g., Qinghai: 38.4 t; Ningxia: 37.8 t; Inner Mongolia: 35.5 t per capita). These HDIs are equivalent or higher than many advanced economies with HDIs over 0.9 (e.g., in Finland with 30.5 t or in the USA with 26.1 t per capita). Most developing countries with a similar, lower-middle HDI have half or less of the MF per capita as Chinese western provinces (e.g., in Brazil with 16.9 t, South Africa with 9.5 t, or India with 3.1 t per capita). China's wealthy coastal provinces/cities have moderate MFs per capita but are still higher than most provinces. However, compared with countries with the same MF per capita, the HDIs of the coastal provinces are slightly lower. Beijing and Shanghai, the most developed provinces, see a higher HDI with high MFs of 25 to 30 t per capita. These results point to different development pathways and relations between MFs and HDIs within China compared with between nations.

Investment shapes different MFs

When compared against other countries, China's GDP has a much higher share of investment expenditure (46%) as a proportion of total expenditure (20% in most OECD countries). By distinguishing consumption- (Figures 2A and 2C) and investment-driven MFs (Figures 2B and 2D), we are able to describe the deviations in the MF-HDI relationship. First, the consumption-driven MF of Chinese provinces shows a good fit with the HDI and the consumption-driven MF relationship of other countries (Figure 2A). The HDI of Chinese provinces ranges from 0.59 to 0.85 in the observed period (see Table S1), corresponding to consumption-driven MF per capita from 2.5 to 16.0 t, which covers almost the same range as for other international countries (2.1 to 15.3 t). However, the investment-driven MF alters the relationship significantly (Figure 2B). In developing China, investments constitute a much higher fraction of GDP than in other countries. In 2012, 52% of the global MF was driven by consumption and 48% was driven by investments; for China, these figures were 33% and 67%, respectively. China was responsible for 47% of the global MF driven by investments in 2012, which was much higher than China's share of the global-consumption-driven MF (20%). The investment-driven proportion of MFs for the western provinces all exceeded 60%, with some reaching 82%.

The divergence between province-level MFs and international country comparisons is almost completely explained by a higher investment MF in Chinese provinces. Investment increasingly dominated the developing Chinese economy through the 1990s and 2000s. Such investment projects translated into a large volume of materials. Figure 2B illustrates that most provinces deviate from the international norms for investment-driven MF per capita. At the same HDI level, Chinese provinces show

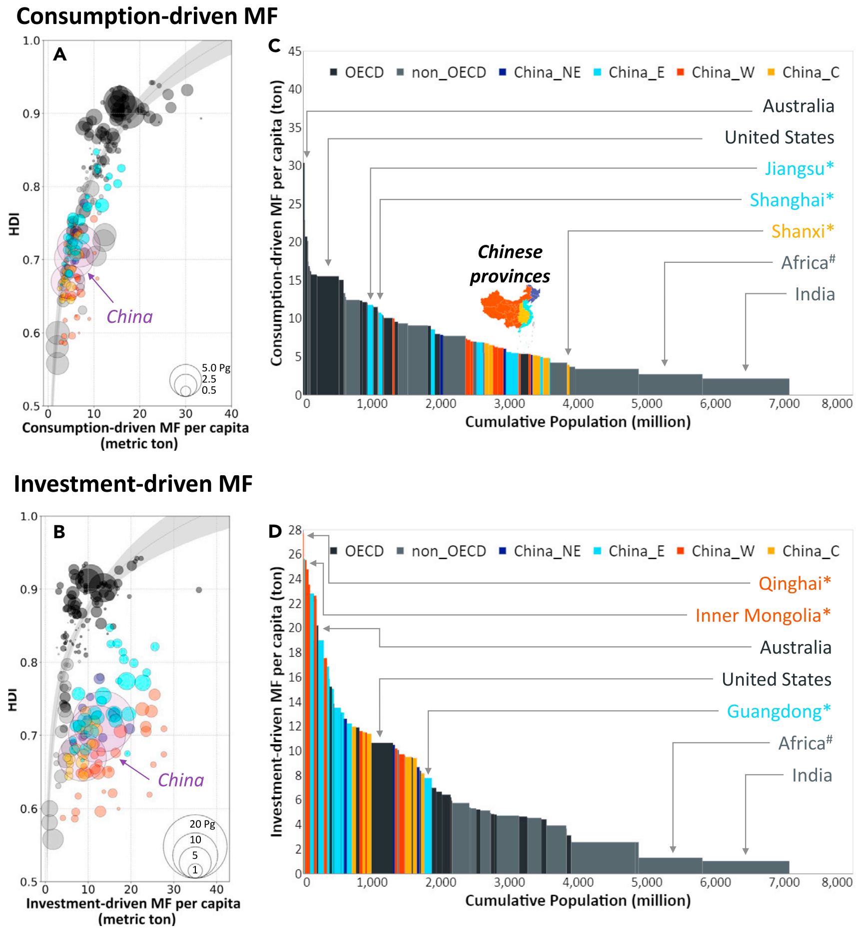

Figure 2. The MF of consumption and investment

(A) The relationship between the HDI and the consumption-driven MF per capita.

(B) The relationship between the HDI and the investment-driven MF per capita. Bubble size represents the overall MF amount driven by the investment of each region.

(C) Consumption-driven per-capita MF by region in 2012.

(D) Investment-driven per-capita MF by region.

The horizontal axis of (C) and (D) is in descending order of MF per capita, and the bar width is the population of each region. The area of the bar is the total MF driven by consumption or investment from each region. In the four subplots, countries are colored in light and dark gray, and Chinese provinces are colored in light blue, dark blue, yellow, and orange.

For (A) and (B), the results are taken from pool regressions of the data in 2007, 2010, and 2012. See marker charts showing the same information as (A) and (B) in Figure S6. The trendline represents the logarithmic relationship between the HDI and the per-capita MF among countries. The 95% confidence interval is indicated by the shaded area.

Data for (C) and (D) are in 2012. The asterisk (*) indicates Chinese provinces and the hash (#) indicates that the Africa bar excludes South Africa (see Tables S3 and S4 for country/region/province lists and group).

a significantly higher investment-driven per-capita MF. This increased MF is most pronounced in western provinces. For example, Qinghai, Inner Mongolia, and Ningxia have an investment-driven MF per capita of over 25 t (Figure 2D). For comparison, their consumption-driven MFs are only ~10 t per capita. This is partly explained by the attempt to leap up the HDI through a dramatic, unusual capital stock accumulation at a unique rate in human history.

Three main factors contribute to this unusually high capital formation: (1) lower population densities, (2) the results of the "Great Western Development Programme," and (3) a unique financial transfer payment system comprising of large fiscal revenue transfers from the East to the West. First, regions with a low population density usually have a higher per-capita resource endowment, which may result in increased, inefficient resource use, and these regions may not see material returns to scale.[3,23,24] This is also reflected in some OECD nations such as Australia, Iceland, and Norway, all of which have relatively high MFs per capita and lower population densities.[3,24] Second, to promote socio-economic development in the least developed western provinces, China's central government set out the Great Western Development Programme, a large-scale investment campaign that lasted almost two decades.[25] In 2008, another stimulus program was launched by the central government to counteract the impacts of the financial crisis. The stimulus package of 586 billion USD led to massive investments targeted mainly on construction and infrastructure-related projects, including nationwide infrastructure improvements and rural development, and substantially improved living standards.[25] Finally, using a special fiscal mechanism—the financial transfer payment system—that comprises enormous transfer payments, subsidies, and tax refunds via the central government between the East and West provinces, played a unique role in attempting to rebalance China's economy[26,27] (see Note S1 for details).

Under these policy contexts, a large and increasing amount of fiscal revenue from the affluent coastal provinces is transferred in the form of investments into western China. Consequently, the share of gross capital formation in the GDP of Chinese provinces expanded significantly. This is especially true for western provinces (in yellow and orange), whose share of the investments in GDP even exceeded 100% in later years due to the financial transfers mentioned above (Figure S9). The investments in capital formation successfully improved accessibility to materials, energy, and living standards: no less than 18 Chinese provinces, including many northwestern ones, jumped from below 0.7 in the HDI group to above 0.7 within just 5 years (see Table S1 for details).

Comparison of MF trends with other countries

Investigating these trends over a longer time period (without province-level resolution) shows a very rapid increase in China's HDI, from 0.55 to 0.75 between 1995 and 2016 (see Figure 3). Meanwhile, China's per-capita MF grew from less than 6 to over 20 t. In general, these trends show that increasing MFs forms part of the requirement for increasing the HDI.[5] The MF

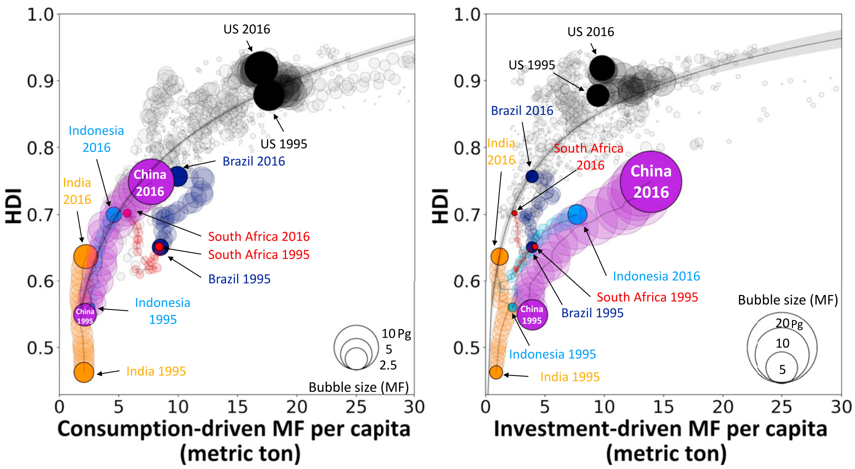

Figure 3. The relationship between the HDI and the consumption-driven and investment-driven MFs per capita

(A) HDI versus consumption-driven MF.

(B) HDI versus investment-driven MF. Bubble size represents the overall MF amount driven by the consumption/investment of each region. The trendline represents the logarithmic relationship between the HDI and the per-capita MF among countries. The 95% confidence interval is indicated by the shaded area.

associated with investments in high-income countries does not show a clear pattern over time. High-income economies (for example, the USA in Figure 3B) generally see a flattening and high per-capita investment footprint throughout the years. After the global financial crisis, investments shrank across most nations, leading to a declining MF in high-income economies such as the USA and the UK (see Figure S10). Many developing countries like China and Indonesia experienced accelerated growth of the investment-driven MF per capita from a very low base before 1995.[28] Their investment-driven MF paths apparently deviated from the general "HDI-MF curve," as Figure 3B indicates. Rapid industrialization and urbanization inevitably bring about growth in material demands, which can be extremely high in some cases, as observed in China's western provinces and the post-World War II periods in high-income nations.[6]

In terms of composition, significant differences between the consumption- and investment-driven MFs exist (see Figure 4B). The majority of the consumption-driven MFs are comprised of biomass and fossil fuels, which are both dissipative in the consumption process. The majority of investment-driven MFs are non-metallic and metallic minerals, which are generally formed into capital goods and accumulated as materials stocks in society[29] (similar to material flows and stocks in the economic-wide material flow analysis framework[6]). Breaking down the investment-driven MFs by biomass, fossil fuels, and metallic and non-metallic minerals per sector (see Figures 4B and S11), we find that the least developed provinces in China (HDI: 0.5–0.6) see a higher investment-driven non-metal footprint per capita (13.2 t) than any other country group (countries are grouped and compared with provinces on the basis of an equivalent HDI level). As the investments in China were mostly directed into construction projects such as capital goods (e.g., real estate building and infrastructure), the construction sector alone drove over half of China's MF. The construction sectors in the least developed provinces (HDI: 0.5–0.7) have MFs per capita ~17 t, higher than any other province or country clusters (grouped by HDI) in 2012 (see Figures S11 and S12).

Outlook for MFs across Chinese provinces

Despite the growth of MFs across many provinces, MFs per capita declined in Beijing and Shanghai, from ~30 t in 2007–2010 to 25–27 t in 2012, largely because of a decreasing share of capital formation in GDP. It will be important to investigate whether other provinces follow the same declining path in the future. Since subnational MF data for China are unavailable for the years after 2012, we adopted two proxy indicators to investigate further: the share of gross capital formation in GDP (considered to be an important determinant of MF;[29] see Figure S9) and per-capita cement production (capturing local construction projects; see Figure S13).

With investment intensity and cement production declining in recent years (Figures S9 and S13), investment-driven MFs may have begun to decline across many provinces. Nevertheless, across western provinces, shares of gross capital formation in GDP continue to climb. A reflection is in Qinghai and Ningxia, where per-capita cement production increased the most among all provinces (at >3 t per capita). On the national level, previous studies reported that China as a whole and many individual provinces have seen a peak in coal consumption.[30] For materials, both the International Resource Panel (IRP) and EXIOBASE models[31] illustrate that the growth in China's national MF slowed to ~4% per year by 2015, down from over 10% at the beginning of the century, resulting in an absolute footprint of ~20 t per capita around 2015 (Figure S14). The consumption-driven MF doubled from ~3 t per capita in 2000 to ~6 t per capita in 2015, along with an increasing annual growth of ~4%–~8% per year. During the same period, the investment-driven MF increased from 4 t per capita to 14 t per capita, whereas annual growth peaked at ~15% in 2010 and declined to ~3% in 2015.

Given the tight correlation of the consumption-driven MF with GDP and HDI, we can expect that China's consumption-driven MF will continue to rise. However, China's investment-driven MF is likely to stagnate as more provinces accumulate sufficient capital infrastructure to support higher HDI levels and the share of investments (capital formation) in GDP decline. As is already happening in Beijing and Shanghai, China overall is likely to move to an "investment to GDP" ratio that is more in line with other countries. Such a reduction after a period of highly accelerated capital investment should also be expected if the correlation between in-use capital stocks and GDP found by Krausmann et al. holds.[6] Declines in investments and related MFs may even be possible if stock saturation effects materialize in the future.[32]

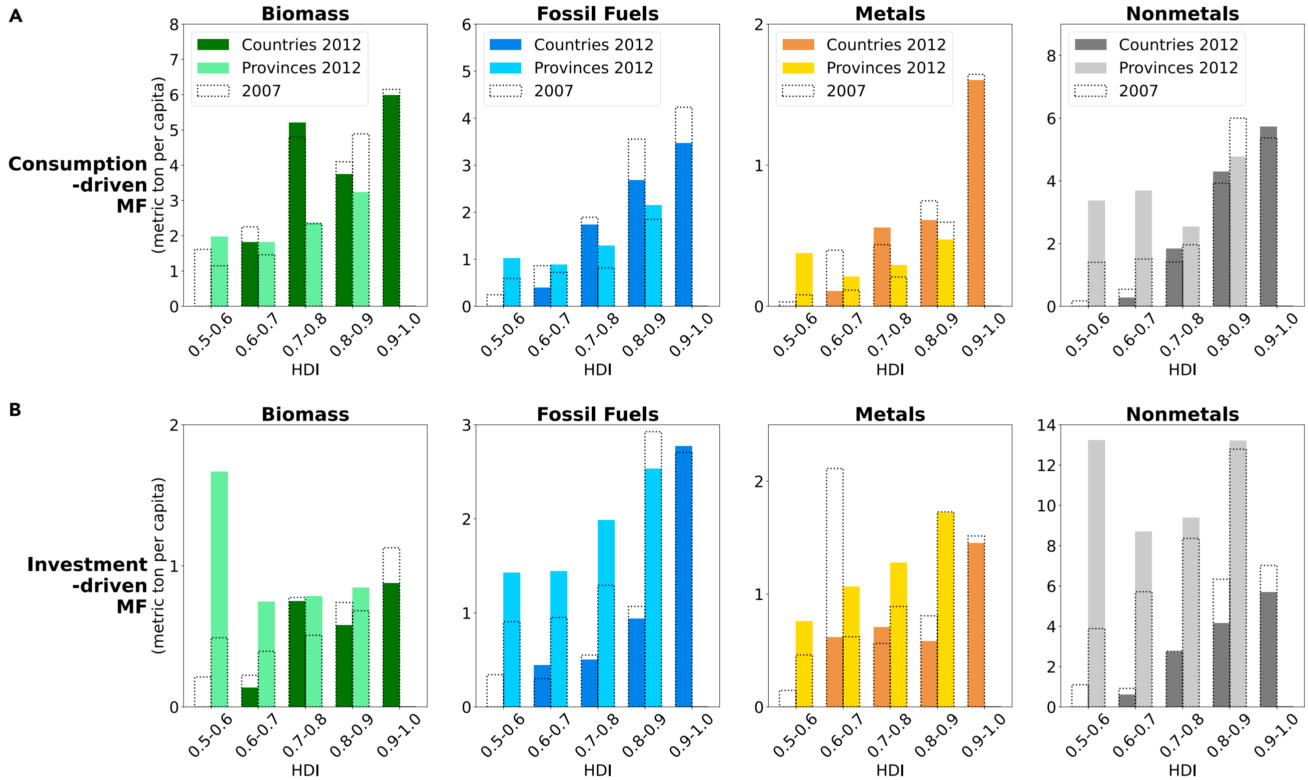

Figure 4. Per-capita MF disaggregated by resource categories

(A) For per-capita consumption-driven MF.

(B) For per-capita investment-driven MF. Country averages are presented in dark colors and Chinese provinces are in light colors. All solid bars are for 2012. Dashed-line bars indicated the value in 2007. Note that no Chinese province has an HDI higher than 0.9 in 2007 and 2012 and no country investigated in this study has a lower HDI than 0.6 in 2012.

The Chinese government has put forward increasingly ambitious climate goals, with a current aim to reach a peak in carbon emissions by 2030 and to achieve carbon neutrality by 2060. Due to the close linkages between material consumption and carbon emissions,[33] reducing MFs may be a prerequisite for achieving the carbon emissions peak.[2] The role of circular economy in reducing material throughputs is emphasized in both the 14th 5-year plan (2021–2025)[34] and the dedicated circular economy action plan (2021–2025).[35] Resource efficiency in China was raised by 26% between 2015 and 2020, and the goal is to further increase it by 20% between 2020 and 2025, according to the plan.[35] It is expected that China's MF is likely to reach its peak soon, which could bolster the actions of climate change mitigation.

DISCUSSION

In this study, we investigated historical relationships between the HDI and MF for consumption- and investment-driven material use. Placing Chinese provinces in a global context, we find that these two different components reveal different insights into material development and highlight some differences between provinces.

First, we provide evidence that intensive investments associated with capital stocks rapidly improved the HDI in Chinese provinces, albeit at the cost of a very high MF per capita. This pattern is conspicuous for developing economies at a particular stage. Besides western provinces in China, we see Indonesia as another example of a high MF and rapidly increasing HDI. It is widely acknowledged that infrastructure and industry are the backbones of the economy and offer the services that human society requires to flourish. Sufficient material stock accumulation provides such prerequisites. The investment-driven material production and accumulation seems to be a fact of current development, but concerns about the future are also widely shared. The large infrastructure investment gaps that need to close in the coming decades[36] present a large challenge both for China and other developing economies: while material-intensive infrastructures provide the foundations for development and wellbeing enhancement, current practices and technologies for building these stocks would inevitably increase (although temporarily) material and carbon footprints. These issues become especially acute in the post-COVID-19 period. As consumption slackens and the global supply chain faces uncertainties, governments may resort to fiscal stimuli to increase governmental spending (i.e., a traditional Keynesian demand stimulus) in the form of infrastructure investment,[37] which would inevitably lead to a higher MF. The perceived need for the rapid implementation of these investment policies may drive poor, short-term decisions and the intensification of low-quality buildings with short life spans.[38–41] Financially, such debt-fueled overinvestments in infrastructure present a serious economic and financial risk[42] (see further discussion in Note S2).

Second, we show that the consumption-driven MF is highly correlated to human development levels, whether in Chinese provinces or across the world. In general, the MF of the consumption of an economy with an HDI near 0.7 (for example, Indonesia, Turkey, and Inner Mongolia in China) is generally around 5 t per capita. This number varies non-linearly with the HDI and can often reach 10 t per capita while the HDI approaches 0.8 (for example, Russia, Hungary, and Zhejiang in China). Some nations with HDIs exceeding 0.9 (for example, the USA, Australia, and Norway) see an MF of consumption exceeding 15 and sometimes even higher than 30 t per capita. These historical relationships indicate that if every economy followed the consumption development pattern of high-income economies, the MF of the world may far exceed the planet's boundaries.[22,43,44] In the future, the largest increase in consumption-driven MFs may occur in developing countries with large populations (see the growth potentials of the economies in gray in Figure 2B). Changing lifestyles and reducing overconsumption of materials is essential, especially in high-income economies where super-rich consumers currently drive high MFs and, perhaps more importantly, set the norms of (over)consumption toward which many others strive.[5] Reducing MFs across high-income countries via circular economy policies and other interventions may reveal a path for development across middle- and lower-income nations (similar to the direct adoption of mobile phones in many lower-income nations, eliding the need for the use of copper in physical telephone lines). Equally, lower- and middle-income nations may create their own paths to material efficiency. In both cases, it will be important to embed circular economy concepts in education across the world.

These insights are derived by teasing apart the consumption- and investment-based MFs of the material (and environmental)-related input-output framework as well as by analyzing historical trends in MFs, estimating future MFs, and comparing MFs among economies. The approach proposed by this study suggests that modeling future MFs across rapidly industrializing nations necessitates a more sophisticated framework going beyond the widely applied assumptions in many existing studies on a direct correlation between GDP and MF or in-use capital stock or stock saturation effects.[18,20,21,29,32] We infer that the development of the consumption- and investment-driven MFs may follow such a paradigm: the early process of development is in high-infrastructure MFs and, afterward, a shift to a higher-consumption MF once stocks are built up. More evidence and future research on such an investment-consumption transition model and on material-reducing actions are necessary.

The additional analytic perspective that MF can bring is of a resource outsourcing pattern.[10] The material transfers embodied in interprovincial and international Chinese trade are extremely large[10] (see Figures S15–S18 and Note S3). A typical outsourcing model of extraction in the West and Central and consumption in the East is observed within China itself (see Figures S15–S26).[10] Since the current footprint calculation framework can only identify the material-embodied flows between primary extraction and final demands, future studies could further explore the intermediate production processes to evaluate the resource efficiency of the industry chains. Additional policies to reduce material use will have ramifications on resource supply chains. As the economies of China's provinces are closely integrated into the global industrial value chain, future work with scenario analyses could shed light on the development of China's material and environmental footprints.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Bing Zhu (bingzhu@tsinghua.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

We used EXIOBASE 3[31,45] as our global input-output model. The Global Material Flow database used for analysis is from IRP.[46] China's Provincial Multi-Regional Input-Output Table (MRIO) is available from the data on the CD attached to the statistical books.[47,48] Regional trade data used here are not public due to the use of proprietary third-party data. The data can be requested from China's customs or from the authors for reasonable purposes. All of the data sources used in the material extensions are indicated in experimental procedures and Table S7 and are openly available to researchers. National HDIs can be obtained from the UNDP database.[49] The Chinese subnational HDI database is provided by the China Institute for Development Planning at Tsinghua University and can be obtained from the report.[12] Population and economic data can be obtained from the World Bank database.[50] All data presented and regression codes used in this paper are available in the Supplemental information and also at Zenodo Deposit: https://doi.org/10.5281/zenodo.5826181

Environmentally extended input-output analysis

When calculating the footprint under environmentally extended input-output (EE-IO), we use the standard Leontief model as presented in Equation 1:[3,51]

$$MF_i = K(I - A)^{-1}y_i \quad \text{(Equation 1)}$$

where MF_i is the MF driven by the final demand y_i. The subscript i represents an individual economy. The equation computes the total MF MF_i of region i (which is driven by its final demand y_i). Consistent with national economic accounting, the final demand y_i in the EE-IO framework can be classified into final-consumption-related items ($y_{i,\,consumption}$) and capital-formation-related items ($y_{i,investment}$). We name the MF driven by consumption-related items the consumption-driven MF, and the MF is driven by the capital formation as the investment-driven MF (under the MF framework, net imports are already reflected in regional material virtual transfer).[52] K refers to the material intensity matrix indicating the domestic extraction (DE) per unit of each economic sector's total output in each sector in each region. $(I - A)^{-1}$ is the Leontief inverse matrix where I is the identity matrix and A is the technical coefficients matrix.

The nested EE-IO model

In our subnational model, we nested Chinese provincial MRIO into EXIOBASE 3[31,45] with the highest common sectoral resolution (see our previous work[10] for details on table linking and processing). We obtained an EE-IO covering 31/30 provinces (31 provinces in 2012 and 30 provinces in 2010 and 2007) and 48 countries/regions. Each region includes 59 sectors in 2012 and 48 sectors in 2007 and 2010. The influence of the sector effect on the results, in this case, is minor (see Figure S27). In the national-level model, we directly employed EXIOBASE, which covers 163 sectors and

48 countries/regions for each year from 1995 to 2016. This model requires a huge amount of data input. At present, as far as we know, the latest and most reliable data of all the databases required for the subnational model are for 2012.

We link the Chinese MRIO[47,48,53] to the global MRIO EXIOBASE.[31] The original Chinese MRIO is limited in sectoral resolution, with 30 sectors in each province in 2007 and 2010 and 42 sectors in 2012. In particular, only five sectors are related to resource extractions and harvesting (agriculture, forestry, animal husbandry and fishery industry, coal mining and washing industry, oil and gas extraction industry, metal mining industry, and non-metallic mines and other mining industries). See Tables S5–S11 for details. Research shows that different physical characteristics aggregated into the same group via monetary units can lead to discrepancies when the MF is calculated.[14] Therefore, we improved the resolution in upstream sectors (where most raw materials first enter the system). We disaggregated the 5 upstream sectors into 23 detailed sectors by assuming the input-output relations of those disaggregated sectors in a province had the same proportion as China's national-level MRIO for those sectors. Other sectors are not altered. Here, we describe the mathematical expressions and details of the disaggregation procedure. We give an example for the splitting of sector 1 (agriculture, forestry, animal husbandry and fishery) of the original Chinese interprovincial input-output table (IOT) into 9 disaggregated sectors (the process for splitting other sectors followed the same approach).

In our model, $Z_{cI,J}^{r,s}$ is the original intermediate demand matrix of Chinese interprovincial IOTs, representing the flows from sector I in province r to sector J in province s (see Figures S28 and S29, where i, j = 1–41 and r, s = 1–31). $Z_{ei,j}$ is China's intermediate demand matrix in the global MRIO (GMRIO) Table from EXIOBASE, representing the domestic flows from sector i to sector j in China (where i, j = 1–59). We can divide the original intermediate flows related to sector 1 in $Z_{cI,J}^{r,s}$ into two parts (see Figures S28 and S29) to obtain the intermediate flows of the 9 disaggregated sectors in the matrix $DZ_{i,j}^{r,s}$ of the nested EEIO model (see Figure S29, where i, j = 1–59 and r, s = 1–31).

Part I below represents the intermediate flows among the 1–9 disaggregated sectors (split from sector 1: agriculture, forestry, animal husbandry and fishery) and the other 1–23 disaggregated sectors. Part II below represents the intermediate flows between the 1–9 disaggregated sectors (splitting from sector 1: agriculture, forestry, animal husbandry and fishery) and the 25–59 sectors that do not need to be disaggregated.

Part I: the intermediate flows that map the 1–9 disaggregated sectors to the 1–23 disaggregated sectors are given by Equation 2:

$$DZ_{i,j}^{r,s} = Z_{c1,J}^{r,s} * \frac{Z_{ei,j}}{\sum_{j=a}^{b}\sum_{i=1}^{9} Z_{ei,j}} (i = 1 \sim 9, j = 1 \sim 23, r, s = 1 \sim 31). \quad \text{(Equation 2)}$$

If j = 1–9, then J = 1, a = 1, and b = 9. If j = 10, then J = 2, a = 10, and b = 10. If j = 11–13, then J = 3, a = 11, and b = 13. If j = 14–20, then J = 4, a = 14, and b = 20. If j = 21–23, then J = 5, a = 21, and b = 23.

The intermediate flows that map the other 10–23 disaggregated sectors to the 1–9 disaggregated sectors are given by Equation 3:

$$DZ_{i,j}^{r,s} = Z_{cI,1}^{r,s} * \frac{Z_{ei,j}}{\sum_{i=a}^{b}\sum_{j=1}^{9} Z_{ei,j}} (J = j - 18, i = 1 \sim 9, j = 24 \sim 59, r, s = 1 \sim 31). \quad \text{(Equation 3)}$$

If i = 10, then I = 2, a = 10, and b = 10. If i = 11–13, then I = 3, a = 11, and b = 13. If i = 14–20, then I = 4, a = 14, and b = 20. If i = 21–23, then I = 5, a = 21, and b = 23.

Part II: the intermediate flows that map the 1–9 disaggregated sectors to the 25–59 sectors are given by Equation 4:

$$DZ_{i,j}^{r,s} = Z_{c1,J}^{r,s} * \frac{Z_{ei,j}}{\sum_{i=1}^{9} Z_{ei,j}} (J = j - 18, i = 1 \sim 9, j = 24 \sim 59, r, s = 1 \sim 31). \quad \text{(Equation 4)}$$

The intermediate flows from the 24–59 sectors to the 1–9 disaggregated sectors are given by Equation 5:

$$DZ_{i,j}^{r,s} = Z_{cI,1}^{r,s} * \frac{Z_{ei,j}}{\sum_{j=1}^{9} Z_{ei,j}} (I = i - 18, i = 24 \sim 59, j = 1 \sim 9, r, s = 1 \sim 31). \quad \text{(Equation 5)}$$

Consequently, the 30 (or 42 in 2012) original sectors in the Chinese provincial MRIO are disaggregated to 48 (or 59 in 2012) sectors. The inventory category in the final demand is combined into the capital formation category in the same way that the Chinese provincial MRIO is structured in 2010. EXIOBASE v.3.4 contains 163 sectors. We harmonized these 163 sectors to the 48 (or 59 in 2012) in the provincial Chinese MRIO (see Tables S8–S11 for details).

With the two IOTs having the harmonized sectors, we link the two tables by disaggregating national imports and exports matrices for China (at the national level) derived from EXIOBASE. We disaggregated Chinese national imports and exports matrices into each sector in each province based on the proportion derived from international trade data at the provincial level. The detailed procedures are described in our earlier article.[54] In that article, we described and compared two approaches (i.e., Assuming Proportionality and Trade Data Linkage) to disaggregate the imports and exports matrices. To give a brief overview of this previous research, the provincial-level international trade datasets provided information for each international trade item including the originating country with details such as destination country/province, HS code (Harmonized Commodity Description and Coding Systems) of products, transaction values, physical amounts, company codes, etc. We derived the distribution proportion for every sector in each province in the Chinese regional imports and exports matrices by considering every province as a virtual "country."[55,56] We then took the total flows in the GMRIO (i.e., EXIOBASE) to scale up the Chinese interprovincial IOT and the corresponding relationships in EXIOBASE. For China's (national-level) IOT in EXIOBASE, we used $Z_{i,j}$ to represent the inter-monetary flow from sector i to sector j. For Chinese interprovincial IOTs, we used $Z_{i,j}^{r,s}$ to represent the inter-monetary flow from sector i in province r to sector j in province r. Then, the $Z_{i,j}^{r,s}$ in Chinese interprovincial IOTs were scaled up to $TZ_{i,j}^{r,s}$, which had the same magnitude as EXIOBASE and could be used for connection:

$$TZ_{i,j}^{r,s} = \frac{Z_{i,j}}{\sum_{r=1}^{secNum}\sum_{s=1}^{secNum} Z_{i,j}^{r,s}} Z_{i,j}^{r,s}, \quad \text{(Equation 6)}$$

where *secNum* referred to the total amount of sectors included in the model. Here, we have 59 for 2012 and 48 for 2007 and 2010.

Then, a biproportional adjustment (i.e., the RAS method[57,58]) was employed to balance the IOT. The aim here was to alter the original data as little as possible while keeping the nested GMRIO balanced. As the original GMRIO (EXIOBASE) and Chinese MRIO are already balanced independently (although scaled), they are assumed to be correct, and the imports and exports matrices were adapted to meet the balancing constraint. The linked China-GMRIO includes 78 regions (original 48 counties/regions in EXIOBASE and 30 Chinese provinces/cities) with 48 (for 2007/2010) or 59 (for 2012) economic sectors. All data and programs can be requested from the authors for replication purposes.

Material extraction extensions

When constructing China's provincial DE database, we based it on the methodology and principles recommended by Eurostat[59,60] and IRP's global material database.[61] We have identified the usual four main categories (biomass, fossil fuel, and metallic and non-metallic minerals), 13 subcategories, and 29 specific types of resources. Detailed compiling processes could be viewed in our previous work[10] and Tables S5–S7. The DE values of other countries and regions were obtained from the EXIOBASE environmental satellite account, which is based on the global material flow database of the UN-IRP.[31,61] The allocation of extensions to the sectors of China's economy was a straightforward one-to-one exercise since most material items entering the economic system are from the extractive (harvesting) industries.[31] We compared our DE database and other similar accounts in Figure S30. The total Chinese DE in our province-level database is slightly larger than in the IRP database[31,61] while slightly smaller than that in Wang et al.[62]

HDI and per-capita MFs

The HDI is a composite index measuring the average achievement in three basic dimensions of human development—a long and healthy life, knowledge, and a decent standard of living.[12] We collect the HDI of countries from the UNDP database.[49] The subnational HDIs of Chinese provinces were provided by the School of Public Policy and Management, Tsinghua University, based on joint research by the UNDP, the China Institute for Development Planning at Tsinghua University, and the State Information Center.[12] We employed a simple regression for a specific year (results are presented in Figures S1 and S2) as indicated in Equation 7 and a pooled regression analysis as indicated in Equation 8 (results are presented in Table S2) to map the relationship between HDI (HDI_t) and the per-capita MF (MF_t). The regression equations are as follows:

$$HDI_t = \beta_0 + \beta_1 * \ln(MF_t) + \varepsilon_t \quad \text{(Equation 7)}$$

and

$$HDI_t = \beta_0 + \beta_1 * \ln(MF_t) + u_t + \varepsilon_t, \quad \text{(Equation 8)}$$

where β_0 is an individual MF invariant effect. The coefficient β_1 represents the relative change in per-capita MFs corresponding to the relative change in HDI. u_t is the time fixed effects, and ε_t is the error term.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.12.011.

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AUTHOR CONTRIBUTION

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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