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Substantial increase in China's manufactured sand supply since 2010

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As the world's second most consumed resource, sand is being depleted at an alarming rate. China accounted for nearly half of the world's sand consumption in 2012. Here we present a material flow analysis of sand from 1995 to 2020 that shows China's overall sand supply surged by approximately 400% over the study period, yet the proportion of natural sand dropped from ~80% to ~21% due to the increasing use of manufactured sand. From 2010 to 2020, China's natural sand supply nearly halved due to the strict policies on natural sand mining and the promotion of manufactured sand. This shift demonstrates a possibility for mitigating impacts on natural sand resources during industrialization and urbanization.

Construction of infrastructure is accelerating the depletion of natural sand reserves at an alarming rate[1,2]. In 2015, global sand extraction surpassed 13 billion tonnes per year (Gt yr^{-1}), notably outpacing its natural replenishment rates[3]. Projections suggest that, by 2030, the demand for sand could more than double, reaching between ~20 and 49 Gt yr^{-1}. This surge is largely attributed to population growth and rapid urbanization, particularly in developing countries[4]. Beyond the issue of resource scarcity, unrestricted sand mining poses serious environmental threats, such as riverbank erosion[5], loss of biodiversity[6] and deterioration of water quality[7]. It also leads to illegal labour practices and 'sand mafias'[8].

Previous research has acknowledged the extensive and severe natural sand depletion, as well as its far-reaching consequences[4,9,10]. However, there is still a lack of detailed understanding about the complete life cycle of sand, which includes its extraction, production, usage and disposal. Conducting a thorough material flow analysis (MFA) of sand would illuminate how sand is utilized at each stage of its life cycle and could identify effective strategies for managing sand resources. This is crucial not only for sustainable sand management but also for responding to recent appeals from the United Nations[3,7].

Here, we make an attempt to close this knowledge gap by introducing a dynamic MFA framework to quantify China's sand flow throughout its entire life cycle from 1995 to 2020. This study concentrates on China because it is the largest developing country and accounts for almost half of the world's sand consumption in 2012 (ref. 7). Facing diminishing sand reserves, China's central and local governments have implemented conservation strategies. These include establishing regulations for sand mining management[11], developing the River Chief System[12] and enhancing the National Construction Sand Standard[13]. In this context, we specifically examine the changes in China's sand supply and consumption patterns, as they can assist policymakers in seeking strategies to curb natural sand depletion and related environmental challenges.

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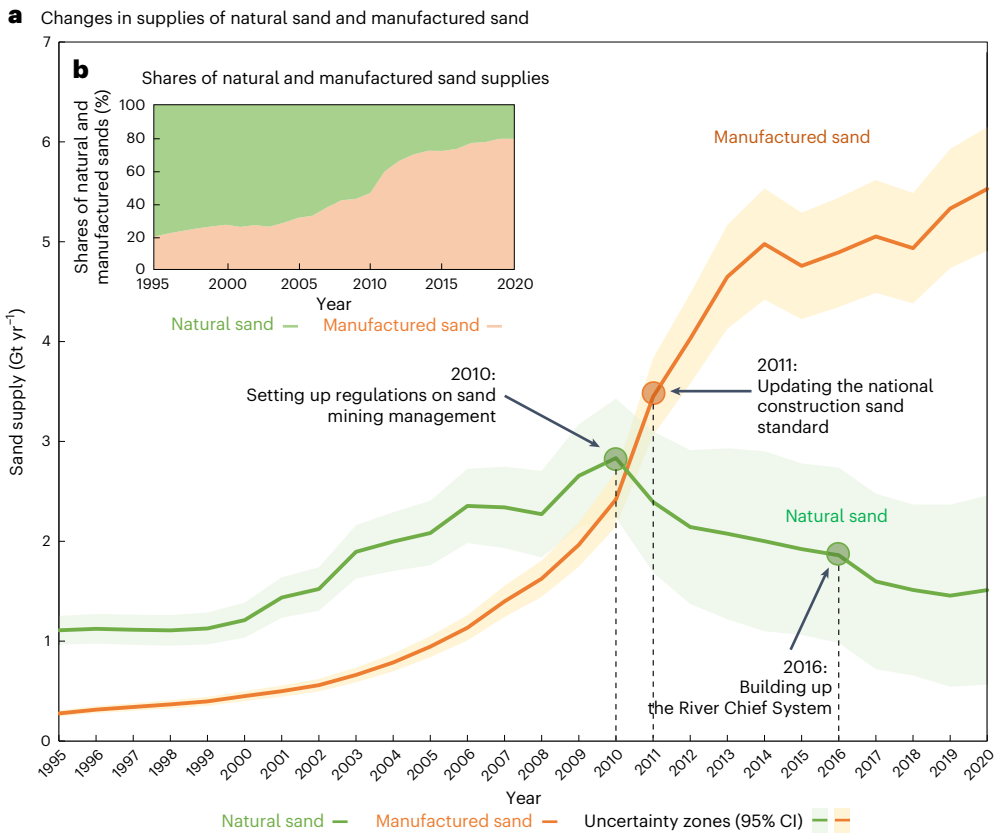

Fig. 1 | Historical trends of China's natural sand and manufactured sand supplies. a, Changes in supplies of natural sand and manufactured sand. **b**, Shares of natural and manufactured sand supplies. The orange and green dots in **a** represent the times when specific sand management policies were enacted. The solid lines are presented as the deterministic results, and the shaded areas indicate the 95% confidence interval (CI) of the estimates. The detailed introduction of China's sand management measures is presented in Methods, and the additional results are presented in Supplementary Information 2.

Our MFA framework is specifically designed to trace national sand flows through five main processes (mining, fabrication, manufacturing, use and waste management), which include over 40 types of sand flow (for example, extraction, production, consumption, losses and trade flows) and their accumulation in 14 final applications (in-use stocks)[14]. Due to the naturally occurring diversity of sand types, this study specifically focuses on 'construction sand', a type that has been extensively studied in previous research[1–4]. Construction sand is further categorized into natural sand (mainly from rivers, basins, shorelines and pits), manufactured sand (mainly from crushed rocks, quarry stones and tailings), and secondary sand (mainly from end-of-life (EoL) buildings). Manufactured sand refers to rock or mine tailings particles that are made by mechanically crushing and sieving[13]. We have identified and synthesized data in statistical yearbooks, official reports and other public information sources covering the full life cycle of sand in China. To enhance the credibility of our results, we further performed uncertainty analysis and validated the results (Methods and Supplementary Information 1).

Our results reveal that China's total sand supply increased approximately fivefold, from ~1.4 Gt yr^{-1} in 1995 to ~7.0 Gt yr^{-1} in 2020, to support its unprecedented urbanization and economic development. During this period, China's sand supply patterns fundamentally shifted, with the dominant source transitioning from natural sand to manufactured sand (Fig. 1a). This shift was accompanied by a range of regulations and policies targeting sand mining restrictions and the promotion of manufactured sand use. China's natural sand extraction had increased rapidly from ~1.1 Gt yr^{-1} in 2000 to the peak point of ~2.8 Gt yr^{-1} in 2010 when China launched its regulation on sand mining in rivers. After that, the natural sand supply nearly halved and then stabilized around ~1.5 Gt yr^{-1}. Its ratio in total sand supply was ~21% in 2020, down from ~80% in 1995 (Fig. 1b).

During the study period, China's manufactured sand increased quickly at an average annual rate of 13%. Before 2000, its manufactured sand supply stayed below 0.5 Gt yr^{-1}, but a surge occurred since 2001, making it exceed natural sand after 2011. Manufactured sand became the major source to support China's growing demand for buildings, roads and other infrastructures, with its ratio in total sand supply above 70% after 2012. This was mainly attributed to China's encouragement of expanded use of manufactured sand in building materials in 2011 (ref. 13). After 2015, China's manufactured sand supply stayed at ~4.7–5.5 Gt yr^{-1}, mainly due to the slowdown of China's urbanization progress.

We further traced China's sand flows throughout the whole life cycle in a Sankey diagram from 1995 to 2020 (Fig. 2a and Extended Data Fig. 1). During this period, China's cumulative supply of natural and manufactured sand reached a total of 108.4 Gt. Notably, due to high shipping costs, most of China's sand use was sourced locally with negligible international trade. Aside from 2.0 Gt of processing losses, approximately 94.0 Gt was used to produce concrete, and 12.4 Gt was used to produce mortar. They were consumed in transportation infrastructure (33.2 Gt), construction (42.1 Gt) and other end-use applications (28.8 Gt), with a total loss of 4.2 Gt during the manufacturing and use phases. From 1995 to 2020, 100.9 Gt of sand was accumulated as in-use stocks, and only 3.3 Gt entered the EoL stage along with obsolete products. Only 0.1 Gt was recycled among these obsolete products, while the remaining 3.2 Gt was landfilled because of various technical and economic barriers. We also specified China's intermediate products and final applications of sand in Fig. 2b and Fig. 2c, respectively. There was a remarkable increase

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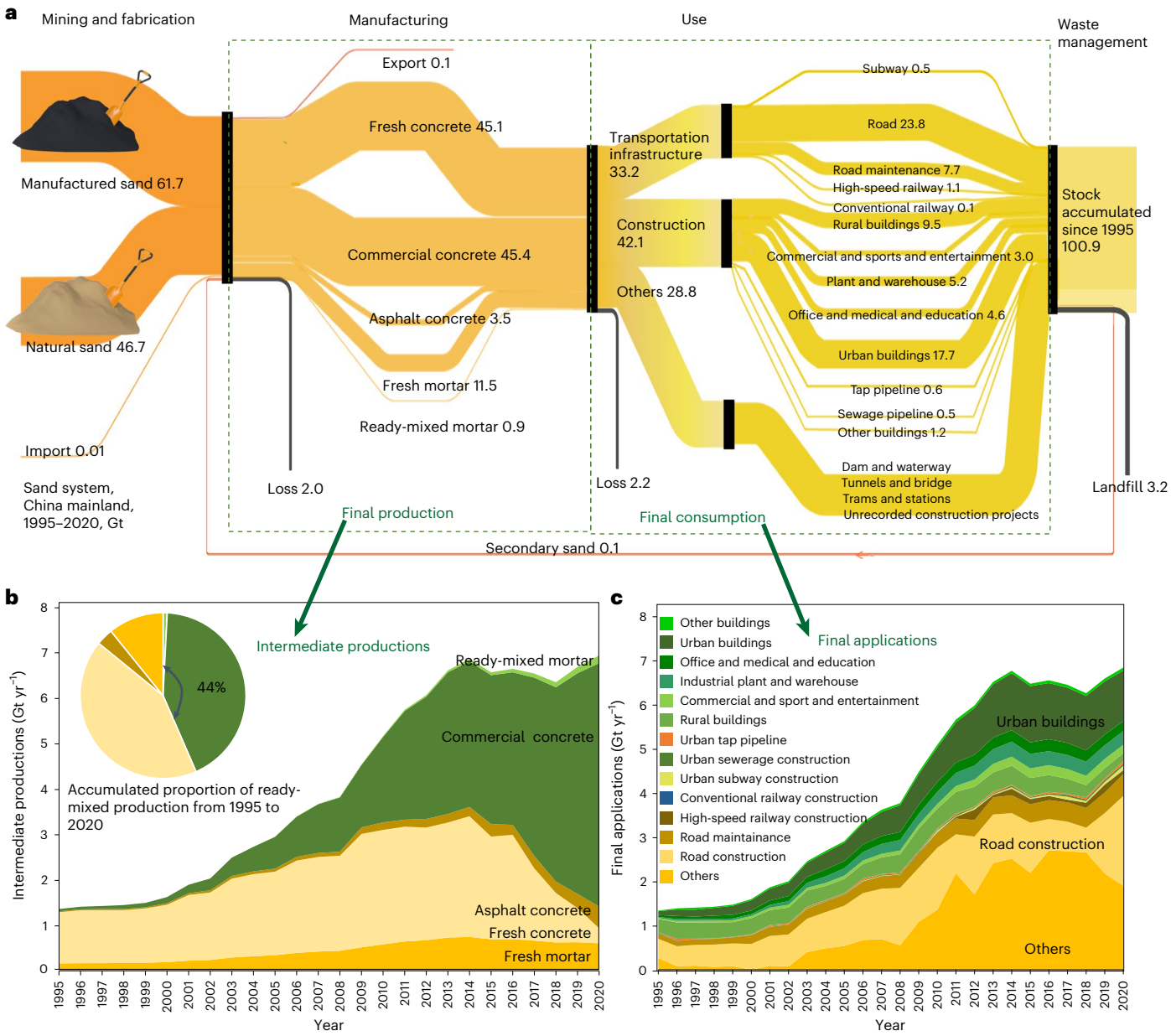

Fig. 2 | China's sand flows from 1995 to 2020. a, The cumulative flows of sand from 1995 to 2020, system boundary: sand system, China, 1995–2020, Gt. **b**,**c**, Detailed results for intermediate products (**b**) and final applications (**c**) in each study year, China, 1995–2020, Gt yr^{-1}. Note: in this MFA, sand is divided into natural, manufactured and secondary on the basis of the source materials. These types of sand are used to produce concrete and mortar and are ultimately consumed in construction projects. In **c**, 'others' mainly include dams and waterways, tunnels and bridges, trams and stations, and other unrecorded construction projects. The material flows may not be balanced due to the treatment of rounding numbers. More detailed results are presented in Supplementary Information 2.

in China's sand consumption starting in 1998, coinciding with the enactment of its housing reform policy[15]. Among the intermediate products, the proportion of ready-mixed mortar and commercial concrete surged from ~4% in 1995 to ~80% in 2020, indicating China's growing appetite for high-performance building materials. At the final application stage, China's sand consumption peaked at ~6.7 Gt yr^{-1} in 2014, then settled in a range of 6.2–6.6 Gt yr^{-1} between 2015 and 2019. This is equivalent to ~4.8 t yr^{-1} per person, more than twice the global average[10]. Furthermore, a noticeable increase in sand consumption occurred after 2019, primarily attributed to road expansion spurred by China's stimulus policies to boost infrastructure investment[16].

Overall, our findings provide evidence that China underwent a substantial shift in its main sand supply source, transitioning from natural sand to manufactured sand during 1995–2020. This shift can be attributed primarily to two key policy factors: (1) strict regulations on natural sand mining[11,12]; (2) the promotion of manufactured sand in building construction, mainly through updates to national construction standards[13]. Notably, such a supply shift was partly driven by economic incentives, since natural sand is more expensive than manufactured sand[17]. Moreover, a few studies have shown that manufactured sand is relatively safer and more sustainable, with lower impacts on the environment when compared to natural sand[18]. Concomitantly, the environmental consequences of this shift should be carefully anticipated and avoided. For instance, if quarrying sites for manufactured sand are developed in ecologically sensitive areas, they may induce adverse impacts and place pressure on ecosystems and biodiversity[6].

China's practice provides a reference to the transition to alternative sand supplies for the world. However, some nations may face challenges in designing effective regulations and securing abundant tailings and waste rocks for producing manufactured sand. These challenges are particularly notable for countries that rely on market-based mechanisms, which often involve fewer direct regulations on natural sand mining. In such cases, given the lower price of manufactured sand compared with natural sand[17] and the global abundance of manufactured sand sources[19], there remains potential to develop a strong market for manufactured sand. This can be achieved through establishing standards, improving awareness among local sand consumers and promoting national cooperation in creating free trade of manufactured sand. Certain countries, such as Canada, Australia and South Africa, have the potential to become key players in the supply of manufactured sand[19].

This study has its limitations and uncertainties. The absence of direct data on natural sand supply and incomplete understanding of sand usage in various downstream products introduce some uncertainties into our findings. To address this, we performed an uncertainty analysis with a Monte Carlo simulation (1,000,000 iterations) for each sand flow, as detailed in Methods. Meanwhile, through comparison and validation with other studies, we found that our key results regarding the proportion of natural sand in the total sand supply align well with previously reported results of natural aggregate[20] (see detailed comparison results in Supplementary Information 2). We also suggest a need for scenario analysis to explore future trends in China's sand demand and the robustness of China's sand supply shift, considering the maintenance needs of existing buildings, newly added stock demand and varying lifetimes of different applications.

The findings of this study indicate a departure from earlier projections[2,4,10], suggesting that the rapid depletion of natural sand deposits may be mitigated. This can be accomplished through a shift from natural sand to manufactured sand. China's experience offers valuable insights for sustainable sand management, particularly for developing economies undergoing urbanization, which will probably fuel future demand for sand.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-024-01501-6.

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Methods

This study mainly applies the dynamic MFA[14] approach to trace the stocks and flows of sand along its life cycle within China annually from 1995 to 2020. The summary of our key steps is provided in this section, and the detailed quantification steps and the corresponding data sources are presented in Supplementary Information 1. The supplementary results can be found in Supplementary Information 2.

Sand definition

In this study, we focus on 'construction sand', which is the main concern in various studies[1–4]. Note that construction sand differs from industrial sand, such as high-purity quartz sand used to manufacture chips. We adopt the definition of construction sand from China's National Standard for Construction Sand (GB/T14684)[13,21], in which sand is defined as a naturally occurring or manufactured material composed of rock particles with a grain size less than 4.75 mm. In addition, the proportions of sand within different sizes are also strictly specified. For example, the proportion of sand with a grain size less than 0.15 mm should not be larger than 5%. It is also notable that China's standard of construction sand is not fully consistent with other countries. In the recently published report by United Nations Environment Programme/Global Resource Information Database Geneva[22], definitions of sand have been reviewed among countries. For example, the European Union adopts the ISO standard (14688-1:2018)[23], defining sand as "a coarse, natural mineral soil which does not stick together when wet and remoulded (that is, non-cohesive) and where the combined weight of 50% of the particles is smaller than 2 mm", and the United States adopts the ASTM D2487-00 (ref. 24) standard: "more than 50% is retained on n°200 sieve (75 µm) and 50% or more of the coarse fraction passes the n°4 (4.75 mm) sieve". Therefore, when carrying out sand MFA for a different country, it is necessary to use the corresponding standards of that country. In addition, since there is no clear definition of sand commodities in the international trade database (https://comtradeplus.un.org/), we assume that sand commodities imported to and exported from China meet the definition of this study.

Sand types

In general, construction sand includes natural sand, manufactured sand and secondary sand. The detailed classification of these three categories is clarified in Supplementary Fig. 1 in Supplementary Information 1.1. Natural sand is a naturally occurring material that is commonly found in the natural environment, mainly including river sand, lake sand, pit sand and desalinated sea sand[13,21]. Manufactured sand refers to rock or mine tailings particles made by mechanical crushing and sieving[13,21]. Note that the tailings in the mining stage can be used to make manufactured sand, such as iron ore tailings, but not all tailings from the beneficiation process can be used as manufactured sand because they may contain high amounts of sulfides or environmentally harmful additives, such as bauxite tailings. In general, manufactured sand has cost advantages over natural sand owing to its lower price in China[17]. Secondary sand refers to the sand that is recycled and reused from EoL buildings and other wastes[25,26].

Sand MFA framework

We apply the dynamic MFA approach[14] to develop a detailed sand MFA framework to trace national sand flows and stocks along its life cycle, which includes five main processes (mining, fabrication, manufacturing, use and waste management), over 40 types of flow (for example, extraction, production, consumption, losses and trade flows) and 14 types of in-use stocks (each as a final application) that are grouped into three categories—transportation infrastructure, construction and others. To improve the transparency of our MFA approach, the quantification framework with detailed steps and data sources for each stock and flow is presented in Supplementary Information 1.2. In the same section, we provide data for key MFA input parameters of sand intensity of buildings, sand loss coefficients and sand intensity of roads, railways, subways and pipelines. The results of our sand MFA are illustrated in a Sankey diagram in Fig. 1a and Extended Data Fig. 1.

Sand demand estimation

Sand demand can be divided into intermediate products (that is, sand in various cement products, including commercial concrete, fresh concrete, asphalt concrete, fresh mortar and ready-mix mortar) and final applications (that is, buildings: urban, rural, commercial and sport and entertainment, industrial plant and warehouse, office and medical and education, and other buildings; transportation infrastructure development: road and road maintenance, high-speed railways, conventional railways and city subways (in bridges, tunnels, foundations, station ancillary roads and so on), urban sewage pipelines and tap pipelines; and other applications). In general, we follow a bottom-up approach to estimate the sand demand in each intermediate product and final application. For each final application, the sand demand $\mathrm{Fin\_Sand}(i,t)$ is estimated on the basis of the building area or road length and its corresponding sand intensity at different layers (mainly from technical reports and literature related to building design; see details in Supplementary Information 1.2) in equation (1),

$$\mathrm{Fin\_Sand}(i,t) = A(i,t) \times C(i,t), \quad (1)$$

where $A(i,t)$ is the building area or road length in project i at year t, and $C(i,t)$ is the corresponding sand intensity per unit of building area or road length.

As for the intermediate product, the demand $\mathrm{Int\_Sand}(j,t)$ is quantified through the volume of various types of cement production with their corresponding sand additives from the designed cement-sand recipe in equation (2),

$$\mathrm{Int\_Sand}(j,t) = B(j,t) \times R(j,t), \quad (2)$$

where $B(j,t)$ is the cement consumption in sand-related cement product j (concrete or mortar) at year t, and $R(j,t)$ is the ratio of sand in sand-related cement product j. Those two demand categories were further cross-checked to obtain the demand of other applications based on mass balance principle.

Sand supply estimation

There are four supply sources to meet China's sand demand: natural sand, manufactured sand, secondary sand and sand from import sources ($\mathrm{I\_Sand}(t)$, quantified on the basis of international trade records; detailed in Supplementary Information 2.3). The secondary sand supply $\mathrm{S\_Sand}(t)$, normally in the form of aggregates from EoL waste back to the concrete and mortar production process[27], is quantified on the basis of China's records of EoL waste from all final applications with its sand intensity (detailed in Supplementary Information 1.2). The quantification of natural sand extraction in China is challenging due to the lack of direct statistics and the potential existence of informal extraction and other unregistered activities. In China, some organizations like China Aggregates Association and other market agencies have collected the records related to the total amount of manufactured aggregates (a mix of sand and crushed stone). Accordingly, we then quantified the manufactured sand $\mathrm{M\_Sand}(t)$ on the basis of its share $\mathrm{MR}(t)$ in total manufactured aggregates $\mathrm{MG}(t)$ at year t (detailed in Supplementary Information 1.2) as shown in equation (3):

$$\mathrm{M\_Sand}(t) = \mathrm{MG}(t) \times \mathrm{MR}(t). \quad (3)$$

Based on the mass balance principle, the natural sand supply $\mathrm{N\_Sand}(t)$ at year t can be obtained with equation (4),

$$\mathrm{N\_Sand}(t) = \left(\sum_j \mathrm{Int\_Sand}(j,t)/(1-\mathrm{LR}(j,t)\right) - \mathrm{M\_Sand}(t) - \mathrm{I\_Sand}(t) - \mathrm{S\_Sand}(t), \quad (4)$$

where $\mathrm{LR}(j,t)$ is the loss rate of specific intermediate sand product j at year t.

Given the very limited amount of imported sand and secondary sand (details in Supplementary Information 2.3–2.4), we measured the ratio of natural sand $\mathrm{NR\_Sand}(t)$ in the total amount of natural and manufactured sand as one key indicator to show the sand supply transition in equation (5):

$$\mathrm{NR\_Sand}(t) = \mathrm{N\_Sand}(t)/(\mathrm{N\_Sand}(t) + \mathrm{M\_Sand}(t)). \quad (5)$$

Uncertainty analysis and result validation

Despite the best available data, our MFA still exhibits certain uncertainties, mainly due to the lack of direct natural sand supply data as well as incomplete knowledge related to the sand intensity of various downstream products. Similar to other studies[28,29], we derived our quantitative uncertainty estimates of model inputs based on their data quality at three confidence levels (for example, high, medium and low; see details in the data sources for sand MFA in Supplementary Information 1.2) and applied Monte Carlo simulation (1,000,000 iterations) to quantify the uncertainties of each model result for final demand, intermediate demand and supply trends. The detailed uncertainty results are presented in Supplementary Information 2.6. We further validated our results with other available data shown in Supplementary Information 2.7, mainly the ratio of natural sand $\mathrm{NR\_Sand}(t)$ to total sand supply. Our results are supported by reference literature, which states that manufactured sand has been the dominant source for China's sand supply. In general, our results of natural sand's proportion to the total sand supply have a high compatibility with other diverse sources, including a study on China's natural aggregate[20], and some government reports stating that "the manufactured sand has gradually replaced natural sand to become the main source to meet China's sand demand"[30,31].

China's unreported natural sand supply and trade

Based on the mass balance principle, we estimated the historical trend of China's natural sand extraction, which might or might not include unreported (illegal) domestic mining and unreported trade of sand. Considering China's River Chief System was proposed and implemented in 2003 partly to prohibit illegal natural sand mining (see China's River Chief System to prohibit illegal natural sand mining in Supplementary Box 1 in Supplementary Information 2.5) and illegal sand mining or trade has been included in the 'Criminal Law' of China[32], large-scale illegal mining has been eliminated from the mainstem of the Yangtze River. For this dominant sand mining region in China, only small-scale illegal nighttime mining activities can be found[33]. We consider the proportion of illegal mining and unreported trade to be very limited compared with the huge amount of total sand supply.

China's sand management measures

On the supply side, China's early national sand management tools were the prohibition policies of natural sand mining, such as establishing forbidden mining areas and setting sand mining registration systems[11] (Supplementary Information 2.5). Since 2016, China has further strengthened its regulatory policies on the illegal mining of natural sand[34]. It is worth noting that China has not slackened its control of natural sand at any stage of development. On the demand side, the policy for promoting efficient sand products (ready-mixed products) was published to improve the quality of sand products and reduce sand loss. Since 2011, the national recognition policies, particularly the updated standard of construction sand (GB/T14684-2011)[13], have notably promoted the development and use of manufactured sand. At the same time, China has gradually strengthened the management of manufactured sand (mining, production and transportation) and has begun to guide the development of secondary sand[35].

Data availability

The data used in this study are presented in Zenodo at https://doi.org/10.5281/zenodo.12507736 (ref. 36).

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Author contributions

H.W., P.W., W.-Q.C. and J.L. conceived the study. X.Z., P.W. and H.W. performed the analyses, with support from H.S., Y.L. and F.M. on datasets and from T.F., H.S., A.T., Y.Y., M.A., C.Z., Q.Y. and C.B. on analytical approaches. W.-Q.C., J.L., Y.-G.Z., H.S. and T.D. advised the policy implications. H.W., P.W., A.T. and X.Z. led the writing with input from all co-authors. All co-authors reviewed and commented on the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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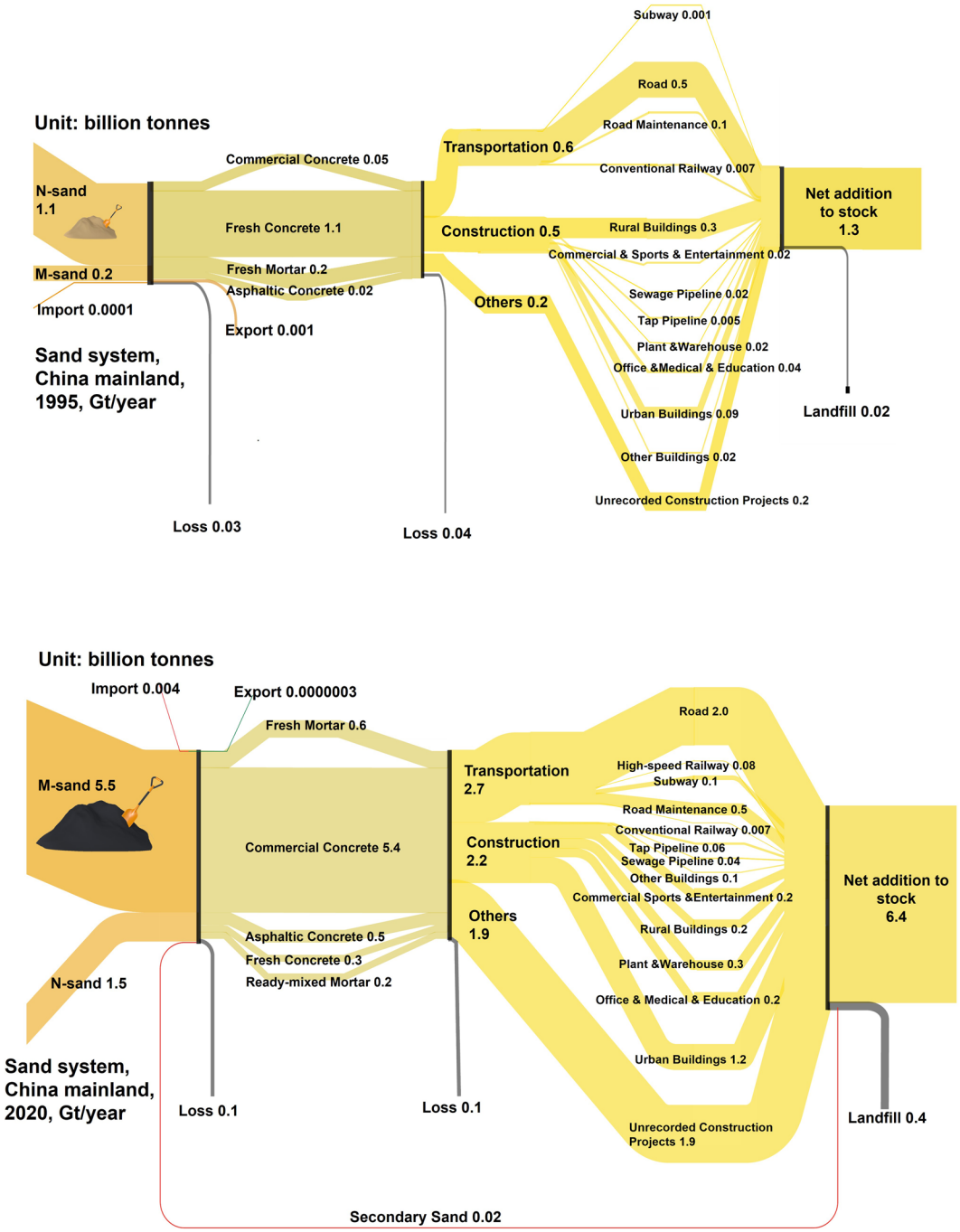

Extended Data Fig. 1 | Sankey diagram of China's sand cycles in 1995 and 2020. Top: Sand cycles in 1995. Bottom: Sand cycles in 2020. System boundary: sand system, China, Gt. Noted, we have no reference for this legend.